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Department of Chemical and Petroleum Engineering

THE RHEOLOGICAL PROPERTIES OF SELECTED

ALBERTA CRUDE OILS

W. Sidjak

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THE UNIVERSITY OF ALBERTA

THE RHEOLOGICAL PROPERTIES OF SELECTED ALBERTA CRUDE OILS

A DISSERTATION

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

FACULTY OF ENGINEERING
DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

by

W. SIDJAK

EDMONTON, ALBERTA

SEPTEMBER 28, 1951.



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THE PROBLEM

The general problem was to determine the rheological behavior of selected Alberta crude oils at varying rates of shear between 0°F. and 70⁰ F. The problem included the study of the effect of previous thermal treatment on the rheological properties.

SUMMARY

This investigation was undertaken to obtain data on the rheological properties of Redwater, Joseph Lake, Excelsior D2, Leduc D2, Golden Spike, Duhamel D2, and Duhamel D3 crude oils. These data could then be used to enable the efficient design and operation of crude oil pipelines. Following a theory and literature review it was decided to employ a MacMichael viscometer to test the oils. The instrument was modified for low temperature work and was then calibrated.

Each crude oil was tested after subjecting it to two thermal histories. One sample was precooled to 0°F . and the other was prewarmed to 70°F . The data obtained were shearing stresses at rates of shear ranging from 4 to 15 sec.^{-1} over the 0°F . to 70°F . temperature range for each crude oil. The shearing stress data were then smoothed by plotting them against the corresponding rates of shear at each temperature. Since the data indicated pseudoplastic behavior at low temperatures they were extrapolated from 4 secs.^{-1} to zero rates of shear by a smooth curve.

Apparent viscosity data were derived from the rate of shear - shear stress curves at the corresponding rates of shear. These apparent viscosity versus rate of shear and temperature data were also smoothed by plotting.

The results indicate that the selected Alberta crude oils at temperatures below 40°F. behave as non-Newtonian liquids, with the exception of Duhamel D2 prewarmed crude oil. Furthermore, previous thermal treatment of the crude oils has an important effect on the rheological properties. Crude oil prewarmed to 70°F. possesses higher apparent viscosities than the same oil precooled to 0°F.

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INTRODUCTION

With the discovery and development of Alberta's oil fields has come the crude oil transmission problem. Oil transmission, by tank truck, railway tank car, or pipeline, can be divided into two classes:- (1) gathering systems from the fields to the markets, usually refineries and storage facilities, and (2) long distance transmission.

Where the proven reserves and/or daily delivery rates do not justify the capital investment in a pipeline, gathering systems usually consist of tank truck or railway tank car transport. However, where large reserves have been proven and the daily output is high, pipeline transmission is the more economical. Long distance oil transmission is also generally accomplished by means of a pipeline.

Transportation by means of tank truck and railway tank car introduces few difficulties. Pipelining, however, is a much more specialized operation. Before the design of a pipeline is begun the general flow characteristics of the oil must be known. Only then is the designer able to size the pipeline accurately and predict the required pumping facilities and the corresponding capacity.

Alberta crude oils are generally waxy in nature; the wax being in solution in the oil at higher temperatures. As the temperature decreases the wax crystallizes out; some of it is deposited on the walls of the retaining pipe while the remainder remains suspended in the oil.

In the course of a Canadian winter crude oils in transit from the wellhead to storage facilities undergo rigorous thermal treatment. Alberta crude oils are usually produced at a temperature of 50°F or higher depending on the production techniques and the temperature gradient from the bottom of the well to ground level. The major portion of Alberta crude oils then goes through treaters to remove sediment, water, and, in the case of Leduc crudes, salt. Here the crude oils are subjected to temperatures varying from 100°F. to 200°F. and higher. On the way to field storage facilities and while in storage the temperature of the oils may fall to as low as 30°F. This final temperature depends upon the ground temperature, the method of burying the pipeline, the length of time that the oils are in storage, and whether or not the oils are heated while in storage. In transit from the storage facilities in the field to the market the oils are cooled still further.

Under such conditions wax precipitation is likely for any oil having a "wax point" of 40°F. or lower. The wax that deposits on the walls of the pipe increases the roughness factor and reduces the effective diameter of the line whereas the wax in suspension

causes an abrupt change in the consistency of the oil.

In such a case, without reliable "temperature-consistency" data, the design of pipelines for waxy crude oils is apt to be more or less empirical, the tendency being toward overdesigning.

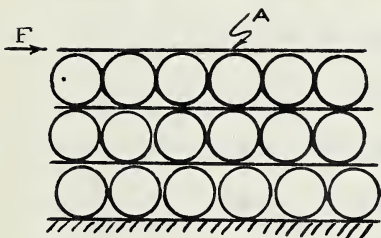
Last year, in an effort to determine the flow characteristics of waxy oils, a research project at the University of Alberta's Department of Chemical and Petroleum Engineering was sponsored by Interprovincial Pipe Line Company. The present work deals specifically with the first part of this project; the laboratory determination of the rheological properties of selected Alberta crude oils. Upon completion of this work the second phase of the program, the determination of the pipeline flow characteristics of such oils, probably by means of a specially designed refrigerated pilot pipeline unit, is to be initiated.

THEORY AND LITERATURE REVIEW

During the past several decades numerous investigators have worked extensively on the determination of the rheological properties of many non-Newtonian suspensions. Very little of this work, however, has dealt specifically with waxy crude oils. There has been no proof that the wax crystals in waxy crude oils are present in sufficient quantities to result in behavior similar to that of non-Newtonian suspension. Emphasis in this dissertation has therefore been placed on a review of all available literature pertaining to waxy crude oil flow characteristics. In addition, the behavior of some non-Newtonian suspensions is described in the event that the crude oils behaved as such.

Newtonian fluids, which are essentially homogeneous, behave according to a predictable pattern. When viscous flow takes place in a pipe the velocity distribution is parabolic. The rate of shear at a given radius is the difference in velocity of two hypothetical cylinders separated by a layer of fluid divided by the thickness of the layer. The rate of shear varies radially across the cross-sectional area. Furthermore, the average shearing stress required to maintain flow is directly proportional to the resulting average rate of shear. Obviously the shearing stress required to maintain a certain rate of shear will vary for different fluids. In other words, the shearing stress depends on the internal frictional

properties of the fluid. Evidently then, the shearing stress divided by the rate of shear is a convenient way of expressing the magnitude of the internal frictional properties. The resulting coefficient, called the coefficient of viscosity, has a unique value at any given temperature.



Sketch 1. Analogy between Newtonian fluid flow and movement of parallel plates separated by spherical balls.

less than that of the first. The plates however are successively nearer to the fixed plate so that the resulting rate of shear is the same for all layers.

The behavior of Newtonian fluids may be summarized by stating Newton's fundamental principles of laminar flow. They are:

- (1) Shear stress, F/A , is uniform in all parts of the film.

The analogy between flow of an infinite layer and of a Newtonian fluid and movement of parallel plates separated by identical spherical balls is depicted in Sketch 1. If a force F is applied to the top plate it moves at a constant velocity and transmits the stress uniformly through each layer of balls whose frictional properties are constant. The velocity of each succeeding plate is obviously

- (2) Shear stress is directly proportional to the viscosity, μ .
- (3) Viscosity is constant regardless of the rate of shear, $\frac{dv}{dr}$.

These quantities are related as follows:

$$\mu = \left(\frac{F}{A} \right) \left(\frac{dv}{dr} \right),$$

where

μ = coefficient of viscosity,

F = tangential force applied to the hypothetical fluid layer,

A = area of the layer,

dv = differential change of velocity of the layer with distance from the wall,

dr = differential distance from the wall.

The coefficient of viscosity μ , which is a constant factor of proportionality, is usually termed absolute viscosity to distinguish it from the more common kinematic viscosity (absolute viscosity/density).

Frequently, however, crude oil and petroleum products do not show a direct proportionality between shearing stress and rate of shear. A possible explanation is that if irregular, non-homogeneous particles are present in the oil they become oriented in such a way as to obstruct the flow of the oil. This is likely in the case of wax bearing crude oils at temperatures low enough to cause phase

separation. As agitation is increased the particles tend to become more and more spherical and to roll like the balls in Sketch 1. The resistance to flow is diminished and a reduction in the viscous properties is apparent. The shear stress is not directly proportional to the rate of shear so that the coefficient of absolute viscosity can no longer be used to define the viscous properties of the fluid. Another term, the apparent viscosity, is often substituted in its place. This is not a constant coefficient but varies with the rate of shear.

The fact that, in some waxy crude oils, wax will crystallize out upon cooling to a low temperature can be ascertained by a visual examination of the walls of a glass vessel in which the crude had been previously cooled. The shape of the wax crystals may have an important bearing on the rheological properties of the oil.

Padgett (8), in his review of research on petroleum wax crystals during the period from 1910-1935, stated that the crystal forms are plate crystals, needle crystals, a mal-crystalline form, and possibly an amorphous form. When needle crystals are formed in oil they grow generally, though not always, from small plates first appearing. Whether needle crystals, plate crystals, the mal-crystalline variety, or mixtures of these result when wax is precipitated from an oil depends upon the inherent characteristics of the wax present, the influence of one type upon another, the concentration of the wax, and on the rate of cooling.

The action of "impurities" or extraneous matter plays

a part in wax crystallization. The needle, mal-crystalline, and amorphous varieties have the power of impressing their forms on the plate crystals, particularly if the concentration of the wax is sufficiently high for the impurity to separate simultaneously with the plates. The associated oil has an influence through its "viscosity"; the higher the "viscosity" the smaller the crystals and the greater the tendency to needle formation.

Both the rate of cooling and the temperature to which the oils have been heated have pronounced effects on the crystallization of the wax. Rapid cooling of oils containing wax has the effects of decreasing the crystal size and promoting needle formation. Cooling the oils, previously heated to a temperature well above that at which all of the wax goes into solution, may cause the formation of crystal clusters.

The behavior of waxy oils, in addition to being unlike that of conventional fluids, is difficult to predict in any given circumstances, particularly at low rates of flow. This is due to several factors. One outstanding reason is that the oils often show quite a different consistency depending on the previous thermal treatment. An instance of this is the gelling property of some waxy oils observed by Bauer and Ruston (4). Their observations indicated that allowing waxy oils to remain stationary in a pipeline chilled to low temperatures would cause the formation of a gel which would be difficult to break.

If the oils are found to have a yield value it can be attributed to the gelling property. The yield value enables them to resist deformation up to a certain applied pressure without any appreciable flow taking place. The simplest example of this is known as the "Bingham Body", whose characteristics will be described in detail later. A body of this type may almost be considered as a soft solid or plastic, since the existence of a limiting shear strength is the essential feature of this class of material.

Apart from the changeable character of the oils described above, the subject is made much more difficult owing to the fact that, whereas there is only one set of laws governing the behavior of true or Newtonian liquids, a separate set of equations must be applied to each distinct type of non-Newtonian liquid of which there are several recognizable classes.

Beale (5) and Alves (1) have classified liquids according to the general type of functional dependence of the shear stress on the rate of shear; that is, according to the general type of shear diagram. There are two main types of classifications: Newtonian and Non-Newtonian.

The distinction between Newtonians and non-Newtonians, and between the main classes of non-Newtonians, is best illustrated by a diagram, Figure 1, showing the rate of shear, or velocity gradient, plotted against the shear stress causing it. Each curve describes the

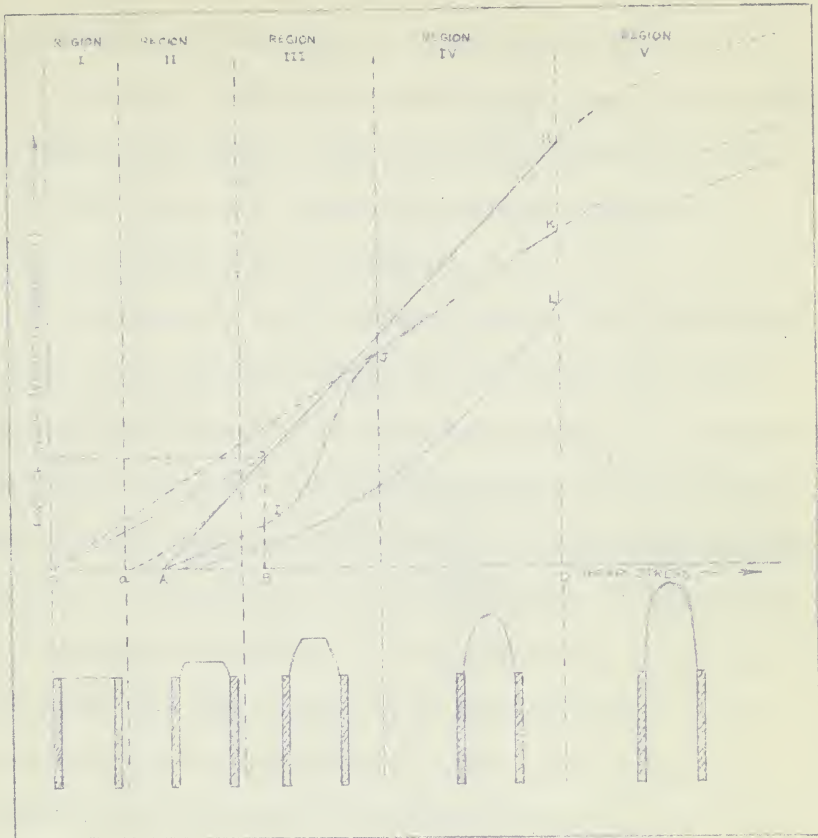


FIGURE 1
THEORETICAL RATE OF SHEAR - SHEAR STRESS CURVES
FOR DISTINCT CLASSES OF NON-NEWTONIAN FLUIDS

internal frictional properties of the liquid in question. The change from "plug" flow to "parabolic" flow, characteristic of liquids possessing a yield value, is also illustrated.

Newtonian liquids are characterized by a shear diagram given as curve OJK, Figure 1. The curve is a straight line commencing at the origin, the reciprocal slope of which is the coefficient of viscosity μ , a constant.

In Figure 1, to the left of point D, are plotted the shear stress - rate of shear curves which represent the fundamental properties of typical non-Newtonian liquids. The simplest of these curves, apart from that for Newtonians, is the straight line AGH which does not pass through the origin and represents an ideal "Bingham Body". The slope of the line represents the reciprocal of the coefficient of rigidity. This coefficient is unique to Bingham bodies. The shear stress OH is that required to cause motion and is referred to as the yield value. Any increase in shear stress above OA causes a proportional increase in the rate of shear.

The equation of this line may be written in the form:

$$\frac{dv}{dx} = \frac{F - f}{\mu} = M (F - f) \quad (\text{c.g.s. units}), \quad (2)$$

where

$$\frac{dv}{dx} = \text{rate of shear or velocity gradient (cm/sec.cm. or sec.}^{-1}\text{)}$$

$$F = \text{total shear stress (dynes/cm}^2\text{)}$$

$$f = \text{shear stress required to start flow (dynes/cm}^2\text{)},$$

$U = \frac{\text{reciprocal}}{\text{slope}} = \text{coefficient of rigidity (poises)},$

$M = 1/U = \text{mobility}.$

The coefficient of rigidity is determined by the reciprocal slope of the line AH, which is constant, and its numerical value in poises is given by dividing the difference between the total shear stress OB and the shear strength OA by the rate of shear OC, all in c.g.s. units.

In practice a perfectly straight shear stress - rate of shear curve for a Bingham body as shown in Figure 1 is seldom realized; and usually there is a certain amount of curvature at the bottom so that it meets the stress axis at a point such as a. This point is often rather indefinite and may be found to be practically at the origin O if small enough rates of flow can be measured. The chief causes of such curvature are the seepage of the oil through the interstices of the wax particles which do not themselves move, and the slippage between the main body of the liquid and the walls of the tube or vessel containing it.

Another type of shear stress - rate of shear curve, which will be discussed briefly, is that represented by the curve AIJK, known as the Ostwald curve. In this case, beyond a fairly definite point J the behavior of the liquid ceases to be a non-Newtonian and the slope of the stress - shear curve becomes constant. The lowest section of the curve AI may be straight, and in some cases this straight section may pass through the origin instead of

cutting the stress axis at A, in which case the liquid first behaves as a Newtonian; then some structural change takes place due to the mechanical forces, and when the change is complete at the point J the liquid again behaves as a Newtonian but of a lower viscosity.

Still another type of shear stress - rate of shear curve is that represented by the curve AL which shows a continuous curvature over the experimental range, and which may or may not pass through the origin. In the case in which it passes through the origin ~~the locus of the~~ curve may be approximated by an equation of the type

$$\frac{dv}{dx} = aF^n$$

when $\frac{dv}{dx}$ and F are the same as before, n and a are constant and n is greater than 1. An equation of this type, however, cannot be accurately true since, as F becomes infinitely large the apparent viscosity tends to zero. Beale's (5) observations indicated that some types of waxy oils and waxes near their melting point have roughly this type of shear stress - rate of shear curve.

Beale (5) found that the yield value of a waxy oil disappears after a certain temperature, owing to wax melting or going into solution, and above this temperature the oil becomes a true Newtonian liquid with a unique value of the viscosity at any temperature. If the same waxy oil is subjected to a different thermal treatment prior to testing it will exhibit a different transition temperature and apparent viscosity vs. temperature curve.

Another factor affecting the rheological properties of crude oils is the pressure to which the oil is subjected. This factor is of considerable importance in the operation of pipelines due to the trend toward higher operating pressures. Anderson (2) analyzed the viscosity vs. pressure relationships of two crude samples by means of a falling ball viscometer. Figure 2 shows the results obtained from testing two crudes: East Central Texas crude, which was one of the lightest commonly handled in pipelines, and Wyoming crude, one of the heaviest.

These data indicate a linear relationship between pressure and viscosity. At higher temperatures, the percent increase in absolute viscosity per 1000 psi is about the same for the two crudes, but at lower temperatures the effect of pressure is much greater on the lighter crude than on the heavier Wyoming crude. Also, for either of the particular crudes, the increase in viscosity due to increased pressure is a greater percentage at lower temperatures.

The foregoing literature review suggests several ways in which waxy crude oils may behave when subjected to varying thermal treatment, period of shearing stress, and applied pressure. There is no theoretical way of deducing the behavior of specific crude oils. The only course to follow is to determine the behavior by testing each crude experimentally with equipment capable of measuring the rheological properties over the range of temperatures and applied pressures commonly encountered in pipelines. Since the present project

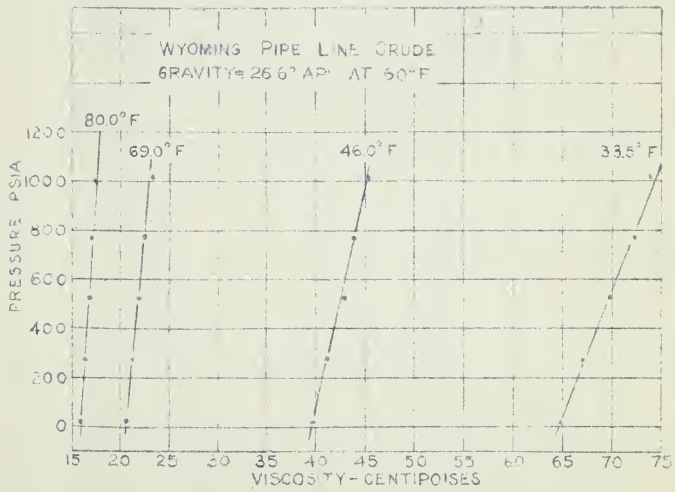
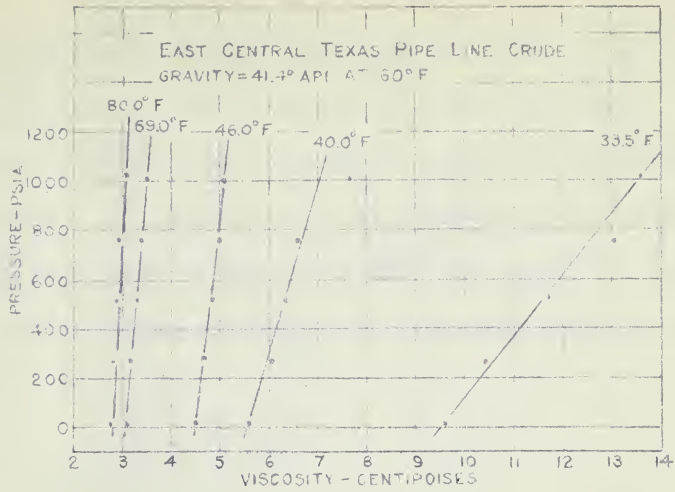


FIGURE 2
EFFECT OF PRESSURE ON THE "VISCOSITY"
OF CRUDE OILS

entails the use of a commercial viscometer this course may be difficult to follow rigorously. Provision for subjecting the crude oil samples to different applied pressures for instance is not a feature commonly incorporated into laboratory or commercial viscometers. It is therefore necessary to review the advantages, disadvantages, and limitations of all the available viscometers and select the one which is most suitable. The summary of such a review and the subsequent choice is presented in the following section.

EXPERIMENTAL EQUIPMENT

Selection of Instrument

Ever since fluid flow became a science the importance of the internal frictional properties of fluids was realized. Since that time many viscometers have been developed for the testing of these rheological properties. Generally the viscometers were developed to meet the need of a specific problem, hence there are very few commercial viscometers in existence that are universal in their applications. The various instruments have been carefully designed and standardized in order to insure comparable results and a high degree of independence upon the personal element of manipulation. This, along with the simplicity requirements of commercial and industrial usage, has served to restrict the useful range of any particular instrument. As a result, anyone contemplating measurement of the rheological properties of a specific liquid must examine all the instruments and select the one most suitable for his work.

The capillary type efflux viscometers are very commonly used in the routine laboratory analysis of liquids. These include the Ostwald, Saybolt Universal, Saybolt Furol, Redwood No. 1, Redwood No. 2, Engler, the Ubbelohde, and the pressure type efflux viscometer. Essentially they measure the time of efflux through a calibrated pipette or aperture. Since the first five viscometers

mentioned indicate only one period of time for the passage of a given quantity of liquid they will not detect any deviation from the constant proportionality between the rate of shear and the shear stress. Therefore, their use is limited to the measurement of the kinematic viscosities of Newtonian liquids.

The pressure type efflux viscometer, however, is capable of measuring the viscous properties of a liquid at varying flow rates, that is, varying rates of shear. In this respect it is the only capillary type viscometer which can be used to observe non-Newtonian behavior. The presence of non-homogeneous particles in the liquid, however, distorts the results of any efflux viscometer in that these crystals, often of significant size, disturb the flow pattern of the liquid through the capillary. Because of this fact efflux viscometers of any type are considered unsuitable for testing waxy crude oils with any assurance of obtaining reproducible results.

Another type of instrument is the falling sphere viscometer, consisting of a vertical tube to contain the sample, and a series of solid spheres of known dimensions. The operating procedure is simple, merely dropping a sphere into the sample tube and measuring the time required to travel the entire length. The time per determination may vary from half an hour to one day. The rate of shear is varied by the use of different diameter spheres. This instrument is capable of detecting non-Newtonian behavior and is

fairly precise in the higher viscosity ranges but its use is restricted due to the difficulty of obtaining very small solid spheres of accurate dimensions.

A modified form of the falling sphere viscometer is the rolling sphere instrument which permits the measurement of much lower apparent viscosities. One such viscometer is the Hoppler which consists of a very accurately made Jena glass tube inclined 10° from the vertical. Such instruments are used chiefly to measure the apparent viscosity under pressure.

The disadvantages in using the falling sphere viscometer for the present problem are the restricted range and the lengthy testing time. The rolling sphere instrument is free of the first disadvantage but the presence of wax crystals on the walls of the tube at low temperatures precludes its use. In any event, it is doubtful whether a suitable temperature control for low temperature work could be incorporated into either one.

Rotational viscometers, of which there are several types, are widely used because of their ability to measure rheological properties at different rates of shear. The MacMichael viscometer employs an outer cylinder or cup rotated by a variable speed electric drive motor. The torque on the stationary inner cylinder or "bob" is measured for various rotational speeds (10 to 45 r.p.m.) by a torsion wire attached to the bob.

The "Precision" Interchemical rotational viscometer is similar in principle but its rotational speed range is considerably greater. A recorder has been developed for this instrument that automatically records the torque for various rotational speeds.

The Brookfield "Synchro-Lectric" viscometer is one of the simplest rotational viscometers. It consists of a cylinder or "spindle" rotated by a variable speed drive electric motor; the outer cylinder is merely a large beaker. The torque on the spindle is measured for various rotational speeds by a calibrated spring. The calibration is given directly in poises; however, this is the viscosity of a Newtonian fluid for the same speed and scale reading. This instrument, though not as flexible or precise as the MacMichael viscometer, provides a rapid means of determining the presence and extent of the various rheological properties.

The Stormer viscometer has an inner cylinder that rotates within a stationary cup containing vertical baffles by the action of a falling weight. The torque is determined from the weight and the radius of the pulley. This instrument is not very suitable for the study of non-Newtonian rheological properties.

Another instrument deserving mention at this time is the Averson "Constant Shear" Viscometer. It is capable of covering a wide range of rheological properties, and is the most versatile of all, but suffers from the disadvantage that it is exceedingly bulky, expensive, and is relatively slow of manipulation. Its use is justified for investigations of non-Newtonian rheological properties

and coefficient of rigidity determinations either in the range of very high values or where, for reasons of exceptional precision requirements the maintaining of absolute control of the rate of shear is essential.

There are numerous other rotational viscometers available. Fisher (6) has discussed the majority of them pointing out their advantages, disadvantages and limitations.

Barnard (3) investigated the "viscosity" and temperature ranges of most of the commercial and laboratory viscometers. The commercial viscometers, which include the Saybolt Universal, Saybolt Furol, Redwood No. 1, Redwood No. 2 and the Engles are capable of testing Newtonian liquids in the viscosity range from 15 to 5000 centistokes at temperatures ranging from 32 to 250°F. Of the two laboratory instruments mentioned, the Ubbelohde has an accurate range of 1.0 to 20,000 centistokes. The capillaries of the Ostwald are interchangeable to give a maximum flow time of 10 minutes. The results should check to within 1 part in 10,000.

Falling sphere instruments are not ordinarily used for liquids with viscosities below 1,000 centistokes. Rolling sphere viscometers are capable of measurements as low as 0.01 centistokes and are frequently used for testing gases. The MacMichael viscometer covers the range from about 60 to 2,000,000 centistokes with a precision of approximately 5%.

It seems then, that a concentric cylinder viscometer is the most satisfactory choice for the immediate problem. The Averson instrument is discounted because of its cost and slowness of manipulation. The Stormer was not considered to be precise enough or flexible enough. The same was true of the Brookfield instrument. This left two instruments, the MacMichael and the Precision, from which to choose. The fact that investment in a new Precision viscometer was prohibitive while a MacMichael was already in the Department simplified the choice.

The only probable disadvantages of the MacMichael viscometer are: (1) the relatively low speeds of rotation, hence the limited rate of shear range, and (2) the possibility of oscillation due to the freely suspended bob. The low speeds of rotation may not be disadvantageous though because of the reduced likelihood of turbulent flow. The second disadvantage may be overcome by leveling the instrument carefully before proceeding with a test. The initiation of oscillation during testing is indicated by the fluctuation of the deflection. The oscillation would then be eliminated by decreasing the rotational speed and releveling the instrument.

MacMichael Viscometer

(A) Theory

As mentioned before, the MacMichael viscometer consists of an outer cylinder or "sample cup" and a stationary inner cylinder or "bob" suspended from a torsion wire, the annulus being filled with sample. The cup is rotated by a variable speed electric motor drive and the deflection of the torsion wire for each rotational speed is indicated on a 0 to 300° dial. Hence the primary data obtained with this instrument are rotational speeds in r.p.m. and the corresponding deflections in MacMichael degrees. The deflections may be converted to torques by multiplying by the wire constant (determined with standard viscosity oils). A knowledge of the cup and bob dimensions enables one to convert rotational speeds to average rates of shear and torques to average shearing stresses.

Reiner and Rivlin (9) have analyzed the laminar fluid flow in the annulus of a rotational viscometer and state that

$$r \frac{dw}{dr} = \phi \left(\frac{T}{2\pi r^2 h} \right), \quad (4)$$

where r = distance from center of bob to some point in the annulus,

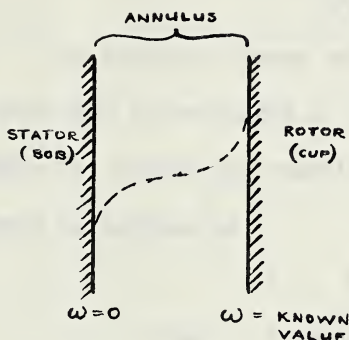
dr = differential thickness of fluid from r to $r + dr$,

dw = change in angular velocity across thickness dr ,

T = moment due to the external forces (torque),

h = height of bob.

The above equation will yield the exact relationship between the rate of shear and the torque if the velocity gradient across the annulus is known. The dotted line in Sketch 2 shows the



Sketch 2. Angular Velocity Gradient Across the Annulus of a Rotational Viscometer.

velocity gradient across the annulus. Furthermore, this velocity gradient varies with different fluids. It is evident that it would be difficult to express the ~~locus~~ ~~of this~~ velocity versus width curve mathematically. In such a case it is impossible to integrate Equation (4) to arrive at the exact relationship between the rate of shear and the torque.

As a result of these conditions it is necessary to work in terms of average rates of shear and average shearing stresses, both evaluated at the same point in the annulus. In order to determine the variation of the rate of shear across the annulus width Weltman (11) conducted experiments in the 200 - 300 sec.⁻¹ rate of shear range with a 2 millimeter annulus width. The results showed that the rate of shear versus the distance from the stator wall to the rotor wall was a straight line relationship. This straight line crossed the midpoint of the annulus at the arithmetic average of the

rate of shear at the stator wall and that at the rotor wall. The equation for evaluating the rate of shear, $\left(\frac{dv}{dr}\right)_m$ at the midpoint of the annulus was given as

$$\text{R.P.M.} = \frac{60 (1/R_b^2 - 1/R_c^2)}{4 \pi} \left(\frac{R_c + R_b}{2}\right)^2 \left(\frac{dv}{dr}\right)_m \quad (5)$$

The shearing stress corresponding to a given rate of shear must then be evaluated at the midpoint of the annulus. Reiner and Rivlin (9) stated the equation for converting MacMichael deflections in degrees to torques as

$$T = K \theta, \quad (6)$$

$$\text{where } K = \frac{\eta w}{\theta S}, \quad (7)$$

and η = coefficient of viscosity of Newtonian standard oil, usually in centipoises,

w = angular velocity, radians per second,

θ = deflection, degrees,

$$S = \text{instrument constant} = \frac{\frac{1}{R_b^2} - \frac{1}{R_c^2}}{4 \pi h} \quad (8)$$

R_b = radius of bob, cms.

R_c = radius of cup, cms.

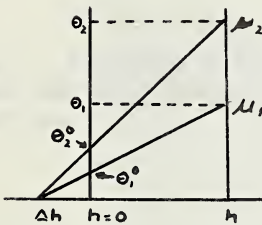
h = depth of immersion, cms.

To obtain the data in terms of average shearing stresses the torque would then be divided by the average radius and the average cylindrical area, both at the midpoint of the annulus.

If the constant S is evaluated on the assumption that all the torque arises from the cylindrical area of the bob an error is introduced because the viscous drag on the bottom of the bob is not taken into account. Greene (7) recommended the following experimental

procedure to determine the "end effect" correction.

A constant rotational speed is set, the bob is immersed to its full length in the oil sample, and the deflection is recorded. The bob is then pulled out in successive steps and both the depths of immersion and corresponding deflections are recorded.



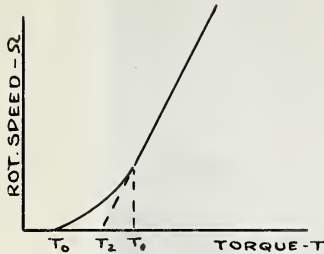
When Θ is plotted against h , as in Sketch 3, a straight line curve which crosses the Θ axis at O_1^0 when $h = 0$ results. This intercept O_1^0 is the amount of deflection due to the bottom of the bob.

Since for a given value of h , Θ varies directly as μ , for a series of viscosities μ , a series of curves μ_1, μ_2 , etc., will intersect the h axis at a common point Δh .

Then, because h is independent of μ , one has only to repeat the above procedure with a series of oils at different constant rotational speeds and depths of immersion to arrive at an accurate value for h . h plus Δh is then substituted for h in the equation of S to compensate for the end effect.

The results of Reiner and Rivlin's (9) analysis of Bingham bodies are presented here because of the possibility that waxy crude oils may exhibit a yield value, that is, a definite applied shearing stress before any flow takes place. This phenomenon is illustrated

diagrammatically in Sketch 4. They stated that the yield value,



$$f = CT_2, \quad (9)$$

where T_2 = the torque intercept of the straight line extrapolation.

$$C = \frac{S}{\ln R_c/R_b} \quad (10)$$

The coefficient of rigidity is then

$$U = \frac{(T - T_2) S}{\Omega} \quad (11)$$

Sketch 4. Consistency curve of a Bingham body made with a Rotational viscometer.

where T is the torque value at rotational speed Ω .

(B) Modifications

(1) Constant Temperature Bath

The conventional MacMichael viscometer was equipped with an adjustable heater which lacked positive thermostatic control. It was therefore decided to modify the instrument so that the sample could be maintained at a constant temperature. The modification, which incorporated Rice's basic principles, permitted the immersion of the sample cup in a bath through which cooling liquid could be circulated continuously from a thermostatically controlled reservoir.

The bath assembly, which was attached to the viscometer without any permanent modifications thereof, pictured in Figure 3 and illustrated diagrammatically in Figure 4, consists of a $\frac{1}{4}$ inch diameter copper inlet tube, an inner, annular intake channel, and an outer annular drain trough.

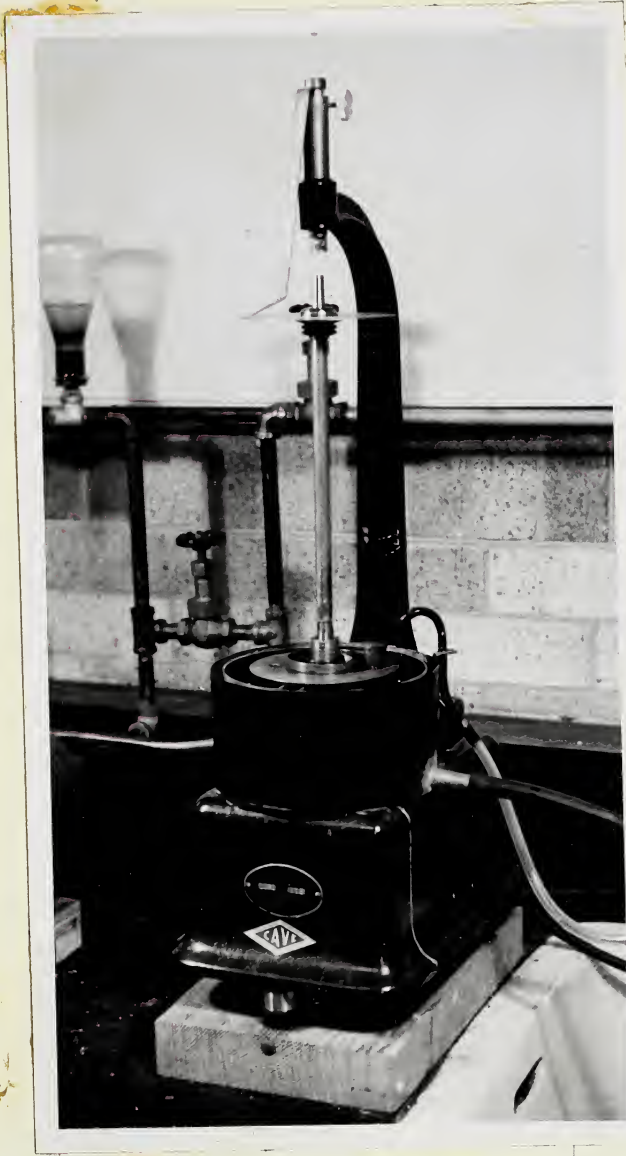
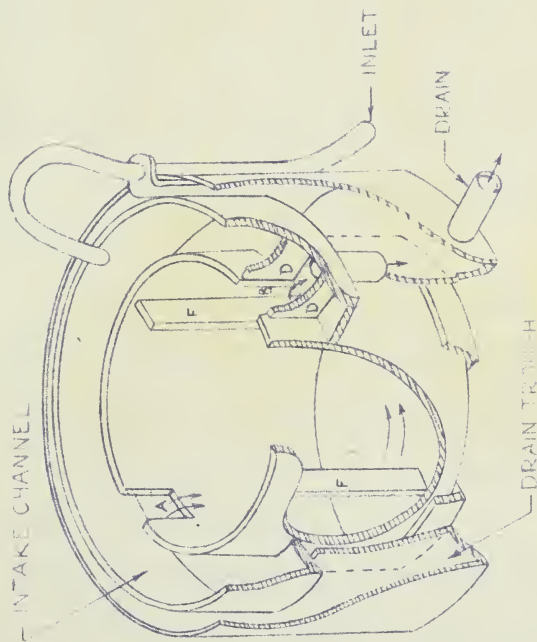


FIGURE 3
MODIFIED MACMICHAEL VISCOMETER





CUT-AWAY VIEW OF BATH ASSEMBLY

NOTES

- A - INLET GATE
- B - OUTLET GATE
- DD - DAMS
- FF - BAFFLES



PLAN VIEW



ELEVATION VIEW

SAMPLE CUP & OVERFLOW TROUGH ASSEMBLY

FIGURE 4

CUT-AWAY VIEW OF MACMICHAEL CONSTANT TEMPERATURE BATH

The intake channel was fabricated of a $5\frac{1}{2}$ inch outside diameter sheet brass cylinder, $1\frac{1}{4}$ inches deep, soldered to a round bottom. The MacMichael bath pot was fitted through a concentric hole in this bottom and was soldered to it so as to form a $7/8$ inch deep channel. Two gates, $5/8$ inches wide, were cut in the opposite sides of the pot and one was dammed off from the channel by two dams shown as (1) in Figure 4. A $3/8$ inch hole was drilled in the bottom between the two dams and a 1 inch long overflow tube was soldered in place.

The annular drain trough consisted of two brazed cylinders of sheet brass, one $4-5/16$ inches outside diameter and 2 inches deep, and the other 6 inches inside diameter and $3-3/8$ inches deep soldered to a ring-like flat bottom. A $3/8$ inch copper return tube was soldered into a hole at the bottom of the external cylinder. To attach the trough to the viscometer, the sliding contact switch was removed from the instrument, and the trough was fastened in place with the screws from the switch.

The sample cup, of $1-1/16$ inch inside diameter and $2-\frac{1}{2}$ inches inside depth was fastened into the machined, closely fitting pot lid so that it protruded $\frac{1}{4}$ inch above the surface of the lid. A $\frac{1}{2}$ inch wide and $\frac{1}{4}$ inch high channel was placed around this projection to form the sample overflow trough.

The path of the bath liquid through the assembly is shown by the arrows in Figure 4. Liquid from the intake channel flows through

gate A into the space in the pot surrounding the sample cup, where it is deflected down and across the bottom of the sample cup by the two vertical fins. The overflow empties through gate B and spills into the drain trough whereupon it is conducted back to the constant temperature reservoir.

(2) Depth of Immersion Control

The bob of the conventional viscometer was suspended from a non-movable suspension shaft. The only way to vary the depth of immersion then, was to vary the amount of sample placed in the cup, a rather inaccurate method.

In order to replace this assembly by a movable suspension it was necessary to remove the dash pot and raise the vertical support by $\frac{1}{2}$ inch. The removal of the dash pot was not thought to promote oscillation if the whole assembly were lined up accurately.

The vertical hole in the top of the support was enlarged to $\frac{7}{8}$ inch diameter and a machined $\frac{1}{2}$ inch inside diameter, $3\frac{1}{4}$ inch long extension sleeve (Figure 5) was screwed in place above it. Following this the whole assembly was adjusted so that its centreline and that of the sample cup were common.

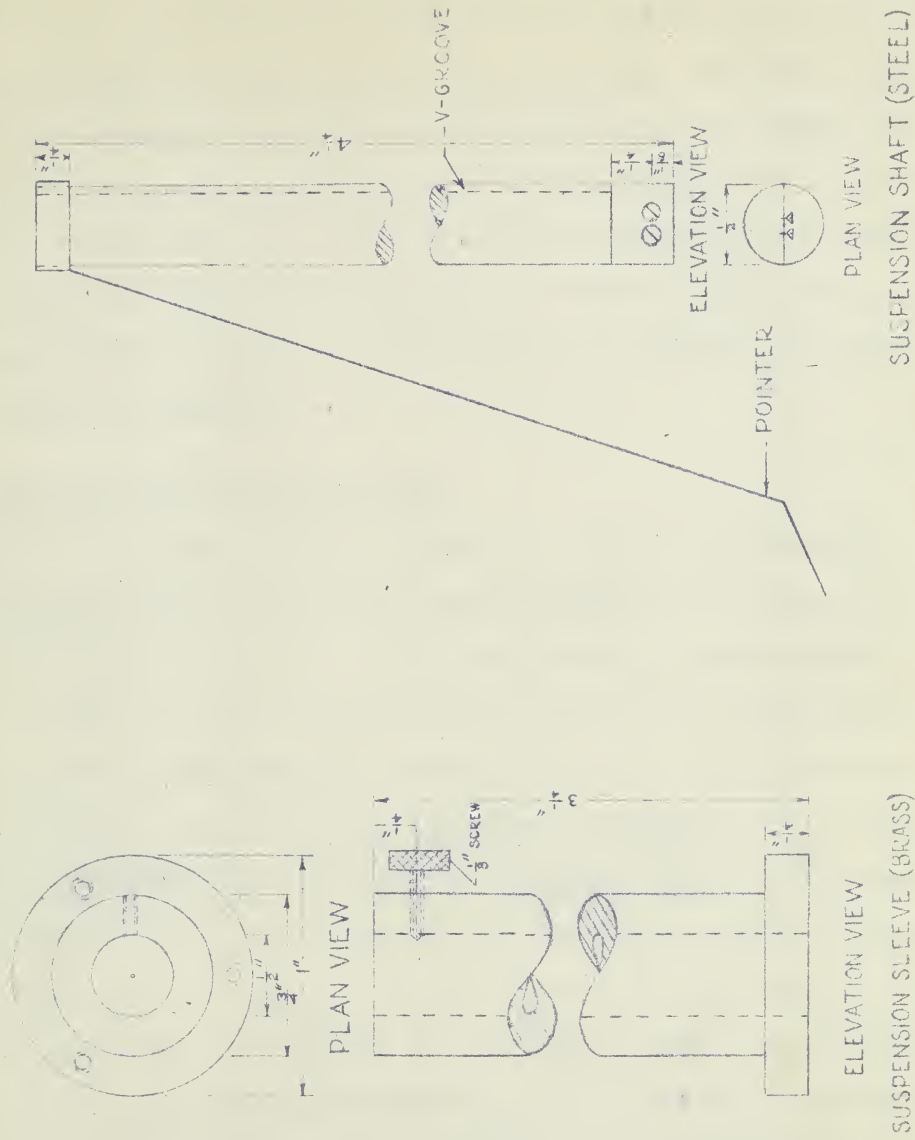


FIGURE 5
MODIFIED SUSPENSION ASSEMBLY OF MACMICHAEL VISCOMETER

A $\frac{1}{2}$ inch diameter steel shaft $4\frac{1}{4}$ inches long was machined with a $\frac{3}{16}$ inch groove running along its length. One half of the cross section of the shaft was cut off over a $\frac{3}{8}$ inch length. Two flat head screws were screwed into the resulting flat face to catch the torsion wire lug. The shaft was held in place in the extension sleeve by means of a knurled screw. A deflection indicating pointer was fitted to the top end of the shaft. The assembly is pictured clearly in Figure 3.

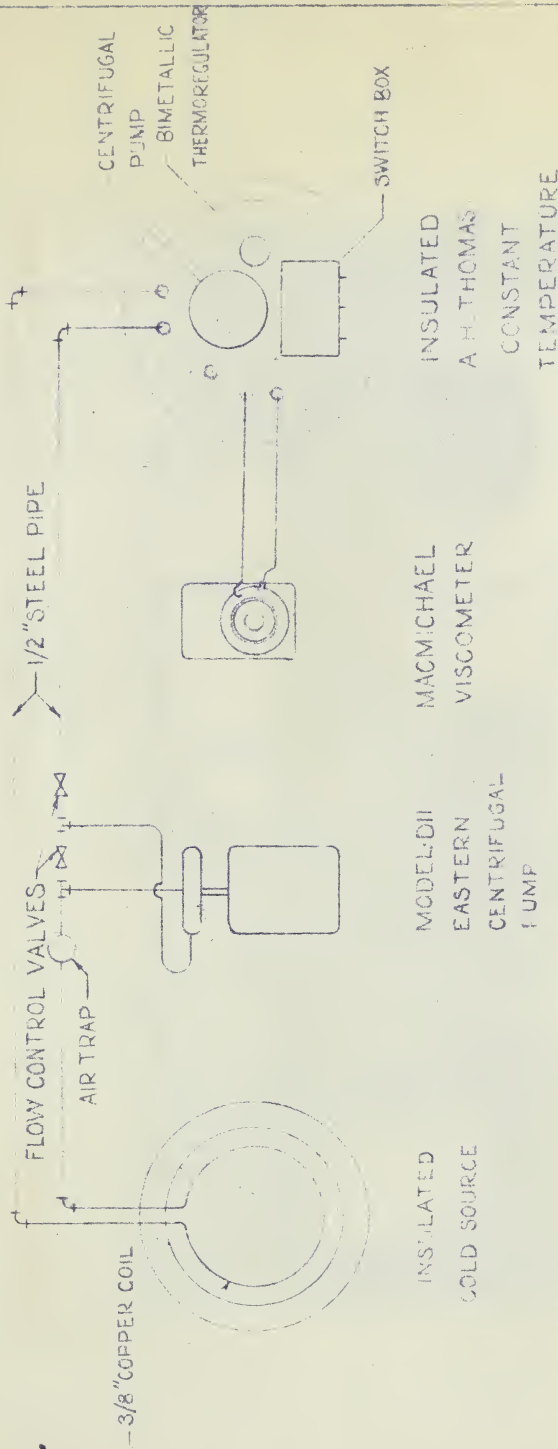
Auxiliary Experimental Equipment

A Thomas constant temperature bath with a circulating pump was used as the constant temperature reservoir. Because of the necessity of changing testing temperatures, ranging from 0°F to 70°F , frequently the mercury thermoregulator was replaced by a -100°F to 350°F bimetallic thermoregulator. The 100 watt auxiliary heater was replaced by a 500 watt heater to reduce the time required in proceeding from one temperature level to a higher one. The entire reservoir was insulated with a 1 inch thickness of magnesia insulation. Three and a half gallons of ethylene glycol-isopropyl alcohol mixture, with a tested freezing point of -20°F , were placed in the reservoir. The discharge of the centrifugal pump, which circulated approximately 1 U.S. g.p.m., was connected to the inlet tube of the MacMichael bath assembly.

The cooling coil of the Thomas bath was connected to the coil of the cold source. This cold source consisted of 16 feet of $\frac{1}{2}$ inch

copper tubing coil placed in a double walled cylindrical vessel of 7 inches inside diameter and 10 inches depth. The $1\frac{1}{2}$ inch space between the walls was insulated with glass wool. This bath was filled with an ethylene glycol-isopropyl alcohol mixture with a tested freezing point of -50°F . The coil of the cold source was connected to the Thomas bath coil with $\frac{1}{4}$ inch steel pipe and the glycol-isopropanol contents (F.P. = -40°F .) were circulated at approximately 5 U.S. g.p.m. with a Model D11 Eastern centrifugal pump.

A recycle control valve was provided to regulate the rate of flow. An air trap in the line on the suction side of the pump insured pulsation free operation. The final complete experimental assembly is illustrated in Figures 6 and 7.



EXPERIMENTAL EQUIPMENT

FIGURE 6
SCHEMATIC DIAGRAM OF EXPERIMENTAL EQUIPMENT

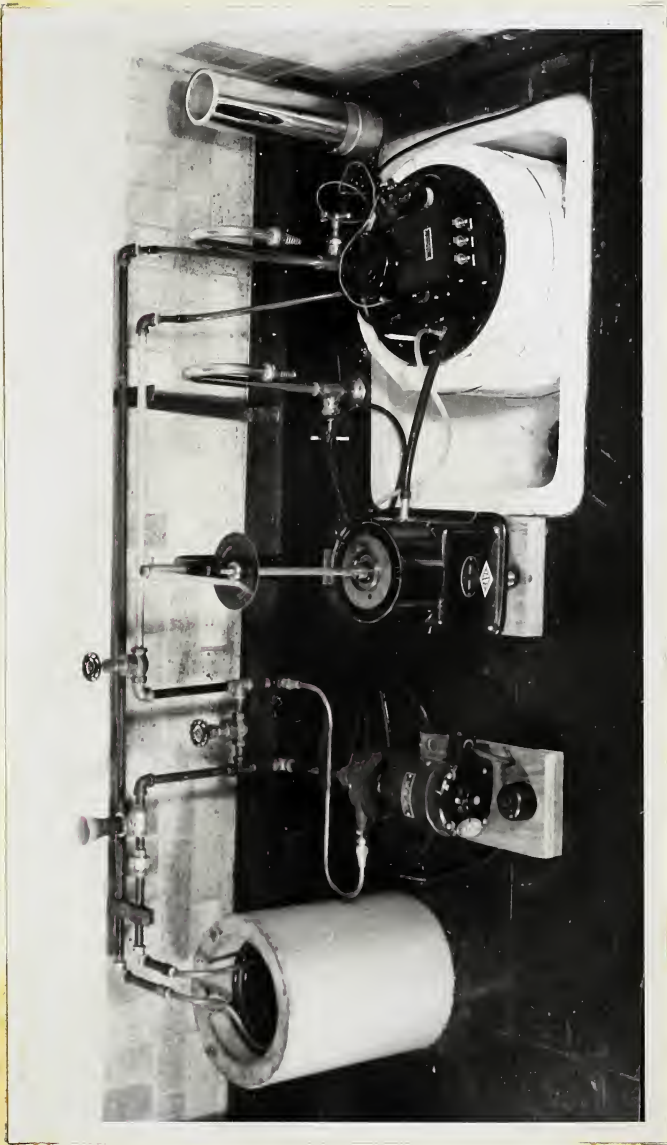


FIGURE 7
EXPERIMENTAL EQUIPMENT



EXPERIMENTAL PROCEDURE

Calibration of torsion wires and end effect correction

The data required for the calibration of the torsion wires and the corrections for the end effect were the same so they were obtained from one test of each of three torsion wires. The first two wires, both 34 gauge, were tested with 149.8 centipoises at 70°F standard oil. The third wire, 32 gauge, was tested with 310.3 centipoise at 70°F standard oil.

Since the viscosity of the standard oils was known at 70°F the equipment was modified to maintain this temperature. The ethylene glycol-isopropyl alcohol cold source was not required for this comparatively high temperature. City water was able to cool the Thomas bath sufficiently to maintain it at 70°F. The cold source, then, was disconnected and the cooling coil of the Thomas bath was connected to the city water supply.

The auxiliary heater of the Thomas bath was switched on and the contacts of the thermoregulator were opened wide. When the temperature of the bath reached 70°F the auxiliary heater was switched off and the thermoregulator was set to regulate at this temperature. The cold water supply to the cooling coil was regulated so that the system was fairly stable, thereby avoiding rapid heating

and cooling which would cause undue chattering of the thermoregulator. When a constant 70°F temperature had been obtained the bath pump was switched on to circulate glycol through the constant temperature bath of the MacMichael viscometer.

The sample cup was filled with the 149.8 cp. at 70°F. standard oil and the bob, suspended from a 34 Gauge torsion wire, was immersed to a depth of 0.6 cm., any excessive overflow being pipetted from the overflow channel.

The MacMichael viscometer was then switched on at its lowest rotational speed for a period of approximately ten minutes to promote heat transfer and allow the sample and bob to arrive at a 70°F. constant temperature. Following this the viscometer was set at the first of five or six equally spaced rotational speeds and the deflection of the bob was recorded. It might be mentioned that rotational speeds were measured by timing the number of revolutions during an interval of about a minute with a stopwatch. The viscometer was then set at each of the succeeding rotational speeds and the corresponding deflections were recorded.

The bob was subsequently immersed to depths of 1.6 cms., 2.6 cm., and 3.6. cm. and the above procedure was repeated at each depth.

The next two wires were calibrated in a similar manner. In the case of the 32 gauge wire the sample cup was emptied, cleaned with benzene, and refilled with the 310.3 centipoise standard oil.

Testing of Crude Oil Samples

Each selected Alberta crude oil was subjected to two thermal treatments and tested for rheological properties over the temperature range from 0°F. to 70°F. in 5°F. to 10°F. increments. one thermal treatment involved cooling the sample to 10°F. below the lowest temperature to be tested by suspending the sample, contained in an Erlenmeyer flask, in the cold source bath. The other sample was warmed under a hot water tap to 10°F. above the highest temperature to be tested.

Temperature control was maintained by connecting the cooling coil of the Thomas bath to the ethylene glycol-isopropyl alcohol cold source and switching on the centrifugal pump. Pieces of dry ice of about half a pound were dropped into the cold source periodically. To arrive at a low temperature more quickly small pieces of dry ice were dropped in the Thomas bath as well. When the desired temperature was reached the thermoregulator was set and the recycle control valve was adjusted to provide a fairly constant bath temperature without undue chattering of the thermoregulator.

In every case the temperature was allowed to go several degrees beyond the desired mark, then brought back to the mark and allowed to remain there until the MacMichael bath had reached the same steady temperature. When proceeding to higher temperatures the cold source was cut off and the auxiliary 500 watt heater was switched on.

The sample, previously subjected to thermal treatment, was placed in the sample cup, and the bob, suspended from a torsion wire, was immersed to a depth of 3.6 cms. This maximum depth of immersion was chosen because it introduced the lowest percentage error. The viscometer was set at the lowest rotational speed, the rotational speed was measured and the corresponding deflection was recorded. The deflections for four other equally spaced rotational speeds were recorded similarly. The temperature was then brought to the next point, equilibrium was attained, and the procedure was repeated. From time to time it was found necessary to lower the bob to maintain a constant depth of immersion because evaporation caused a lowering of the oil level. Two samples of Redwater crude oil, one precooled and the other prewarmed were the first to be tested. It was noted that the deflections resulting from testing the prewarmed sample at low temperatures were much greater than the deflections indicated by testing the precooled sample at the same temperatures. To determine whether this difference resulted from the previous thermal treatments or from faulty manipulation four more samples of the crude were tested. Two were prewarmed, one was precooled as before, and the fourth was cooled to 5°F. and kept at that temperature for 6 hours. At the end of 6 hours the sample was decanted in an effort to obtain the oil relatively free of wax deposit.

The results of the four tests showed beyond a doubt that the difference in deflection was due to the effects of previous thermal

treatment. Therefore, two samples of each of the succeeding crude oils were tested; one was precooled and the other prewarmed.

The crudes tested were, in the following order, Redwater, Joseph Lake, Excelsior, Leduc D2, Golden Spike, Duhamel D2, and Duhamel D3.

The 34 gauge torsion wire was used exclusively because of its greater sensitivity and the fact that it covered the most desirable range of viscosities. It was tested periodically, especially after overranging, to ascertain whether or not it had become overstressed. In some cases, because of the probability of overranging, the depth of immersion was decreased to 2.6 cm. rather than change to a heavier torsion wire.

EXPERIMENTAL RESULTS

End Effect Correction and Calibration of Torsion Wires

The measured depths of immersion, rotational speeds, and corresponding deflections obtained from testing the two 34 Gauge torsion wires are tabulated in columns 1, 2, and 3 respectively of Tables I and II (A). The first wire tested snapped at the lug at the conclusion of the test so it was of no further use. Hence it was not calibrated but the data obtained from it, Table I, were used, together with other data, Tables II (A) and II (B) to determine the end effect correction. Table III (A) lists the data obtained from testing the 32 Gauge wire.

These end effect correction data, Tables I, II (A) and III (A), are shown plotted in Figures 8, 9, and 10 respectively. The point of intersection with the depth of immersion axis is -0.25 cms. in each case. Therefore the correction added to the actual depth of immersion in all further calculations to compensate for the end effect was 0.25 cms.

The data from Tables II (A) and III (A) were next replotted in Figures 11 and 12 respectively. The slopes of the resulting straight lines are indicated on each line. The numerical values of these slopes were then substituted into Equation (7) to evaluate the calibration constants for the 34 Gauge wire and the 32 Gauge wire. Thus for the 34 Gauge wire:

$$K = \frac{\tau_w}{\theta S}, \quad (7)$$

EXPERIMENTAL METHOD

1. General Description of the Experiment

The experiment consists of measuring the rate of change of the concentration of a substance in a closed system. The substance is initially in a state of equilibrium with its surroundings. The system is then disturbed by adding a known amount of the substance. The rate of change of the concentration is measured by observing the change in the concentration of the substance over a period of time. The rate of change is then compared with the theoretical rate of change calculated from the law of mass action.

The rate of change is measured by observing the change in the concentration of the substance over a period of time.

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$$\begin{aligned}
 \text{where } \eta &= 149.8 \text{ centipoises} \\
 &= 0.1007 \text{ lbs./ft. sec.,} \\
 \theta &= \text{MacMichael degrees (300 degrees = } 2\pi \text{ radians),} \\
 \frac{w}{\theta} &= \frac{\Omega \text{ r.p.m.}}{\theta \text{ degrees}} \times \frac{2\pi \text{ radians/revolution}}{60 \text{ sec./min.}} \\
 &= \frac{2\pi \Omega}{60 \theta} \text{ radians secs.}^{-1} \text{ deg.}^{-1}, \\
 S &= \frac{\left(\frac{1}{R_b}\right)^2 - \left(\frac{1}{R_c}\right)^2}{4\pi h} \quad (8) \\
 &= \frac{\left(\frac{1}{0.992}\right)^2 - \left(\frac{1}{1.349}\right)^2}{4\pi h} \text{ cms.}^{-3}, \\
 &= \frac{0.0383}{h} \text{ cms.}^{-3} \\
 &= \frac{1055}{h} \text{ ft.}^{-3} \\
 \text{Therefore K} &= \frac{0.1007 \times 2\pi \times \Omega}{60 \times S \times \theta} \text{ lbs. ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1} \\
 &= \frac{0.01054 \Omega}{\theta S} \text{ lbs. ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1} \quad (12)
 \end{aligned}$$

It should be mentioned that the English Absolute System was used throughout the calculations. The three dimensions of this system are mass (M), length (L) and time (θ). Force (F) is a derived quantity and equals $\frac{Ma}{\beta}$, where a is the acceleration and β is a constant equal to unity.

The calibration of the 32 gauge wire differed from that of the 34 gauge wire only in that 310.3 centipoise (0.2085 lbs./ft.sec.) standard oil was employed in place of the 149.8 centipoise oil.

Therefore the equation for the 32 gauge wire constant is

$$\begin{aligned} K &= \frac{0.01054 \Omega}{\theta S} \times \frac{0.2085}{0.1007} \\ &= \frac{0.0218 \Omega}{\theta S} \quad \text{lbs. ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1} \end{aligned} \quad (13)$$

The calibration constants at each of four depths of immersion are listed in Table II (B) for the 34 gauge wire, and in Table III (B) for the 32 gauge wire. The values were then weighted comparatively; those at the maximum depth of immersion were given the most weight and those at lesser depths were given successively less weight. The resulting average calibration constants were used in subsequent calculations.

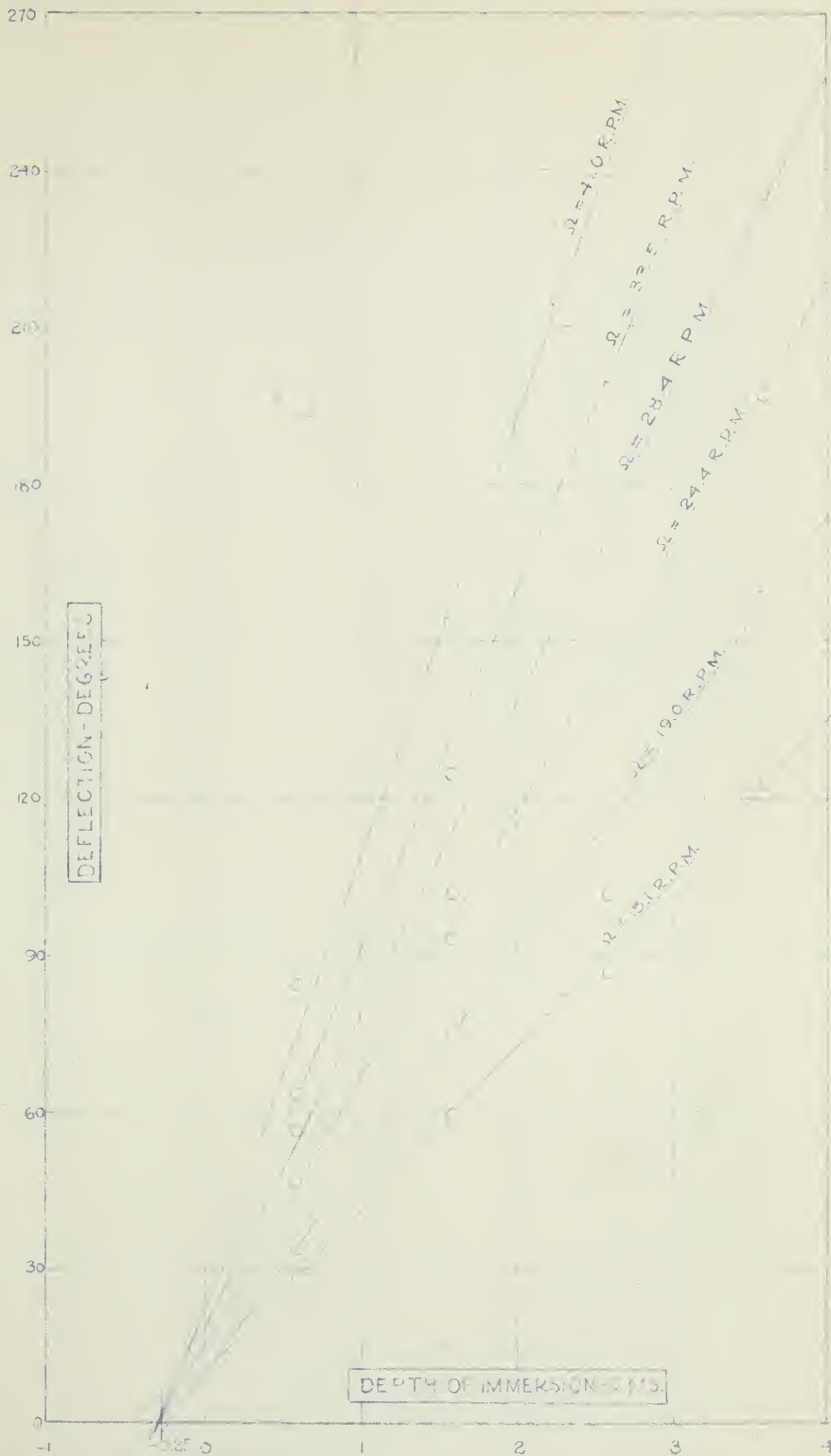


FIGURE 8:-DETERMINATION OF END EFFECT CORRECTION USING A 34 GAUGE TORSION WIRE AND 149.8 cp. STANDARD OIL

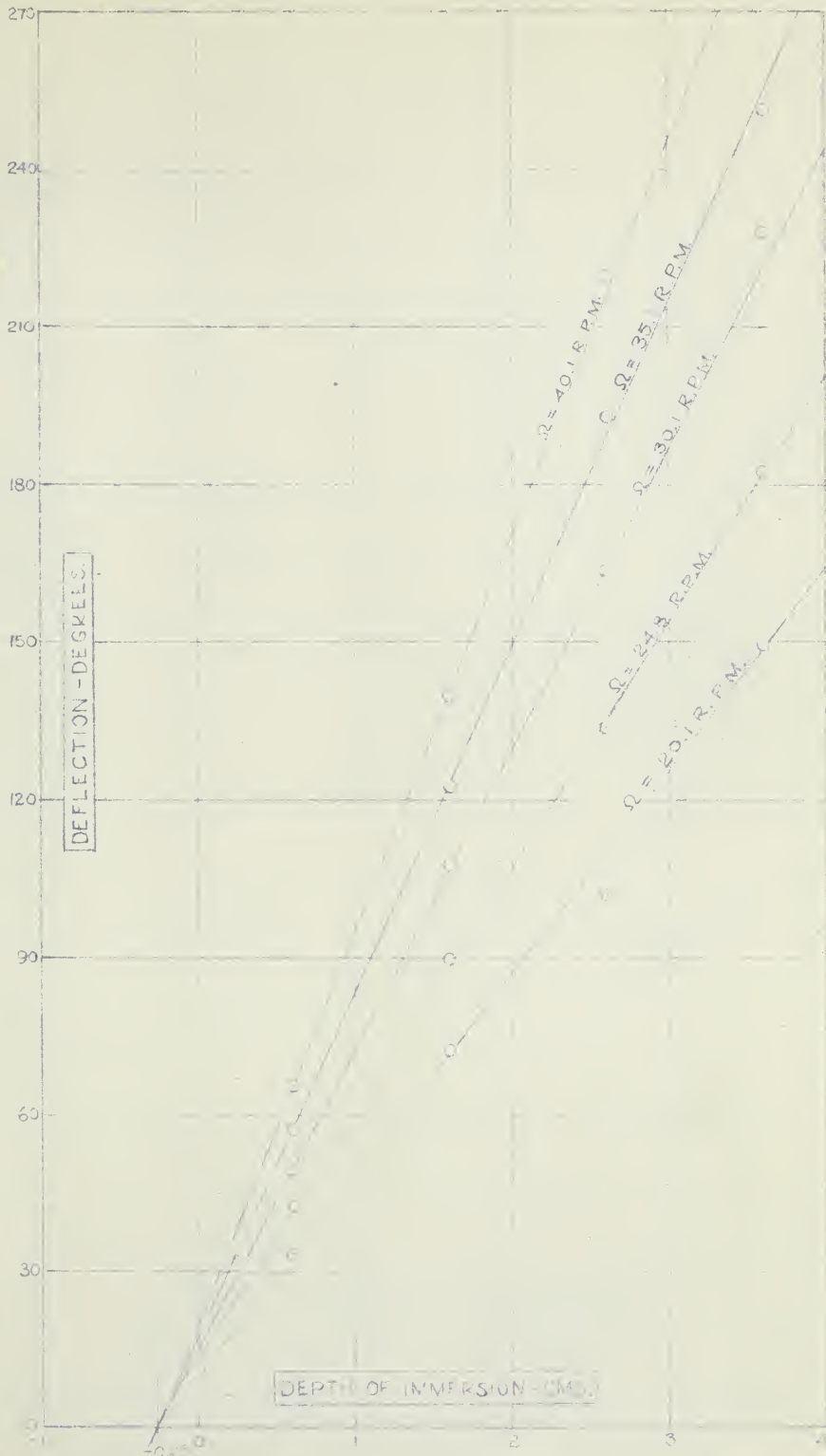


FIGURE 9:-DETERMINATION OF END EFFECT CORRECTION USING A 34 GAUGE TORSION WIRE AND 149.8 cp. STANDARD OIL

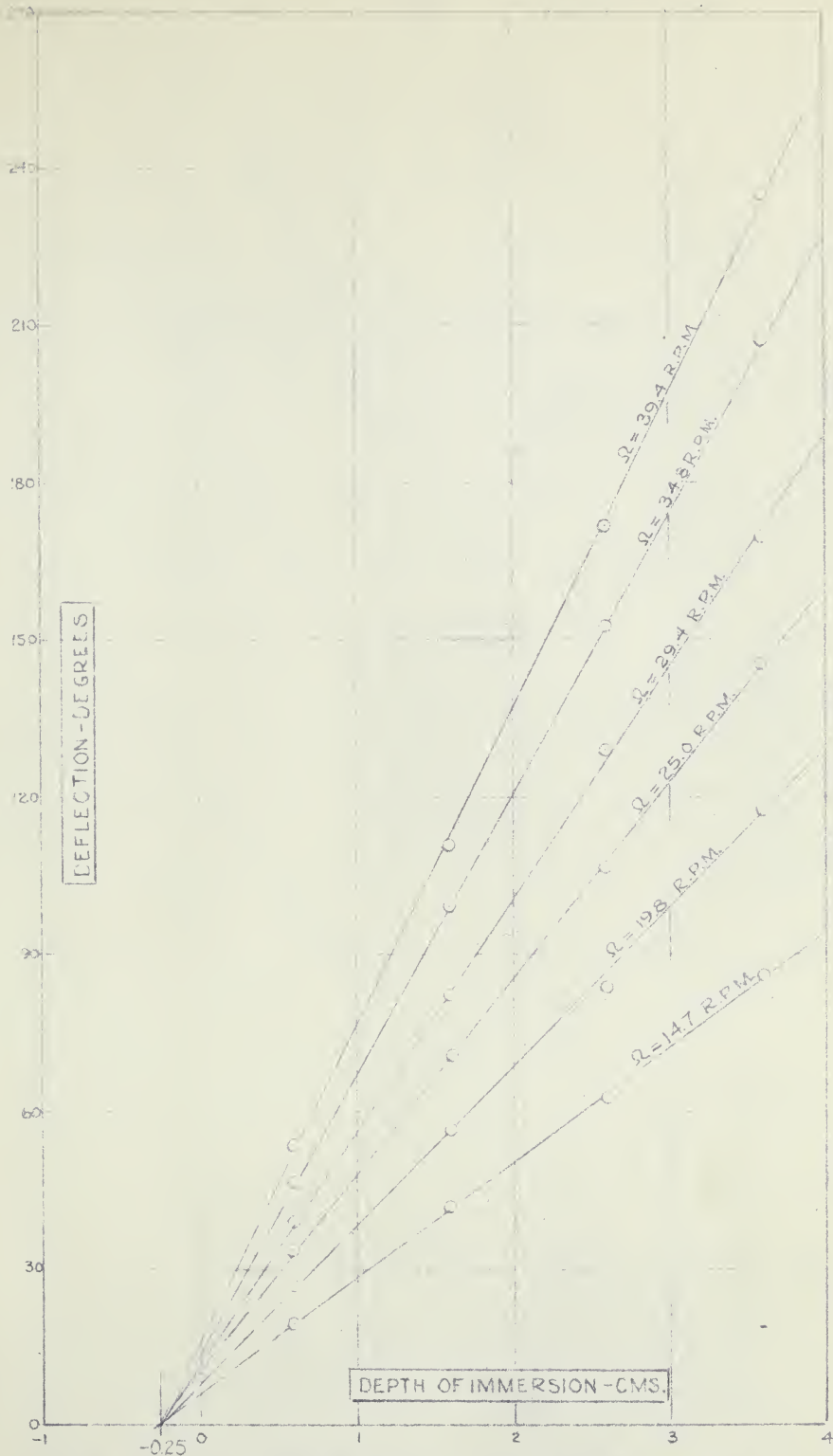


FIGURE 10:-DETERMINATION OF END EFFECT CORRECTION
USING A 32 GAUGE TORSION WIRE AND 310.3 cp. STANDARD
OIL

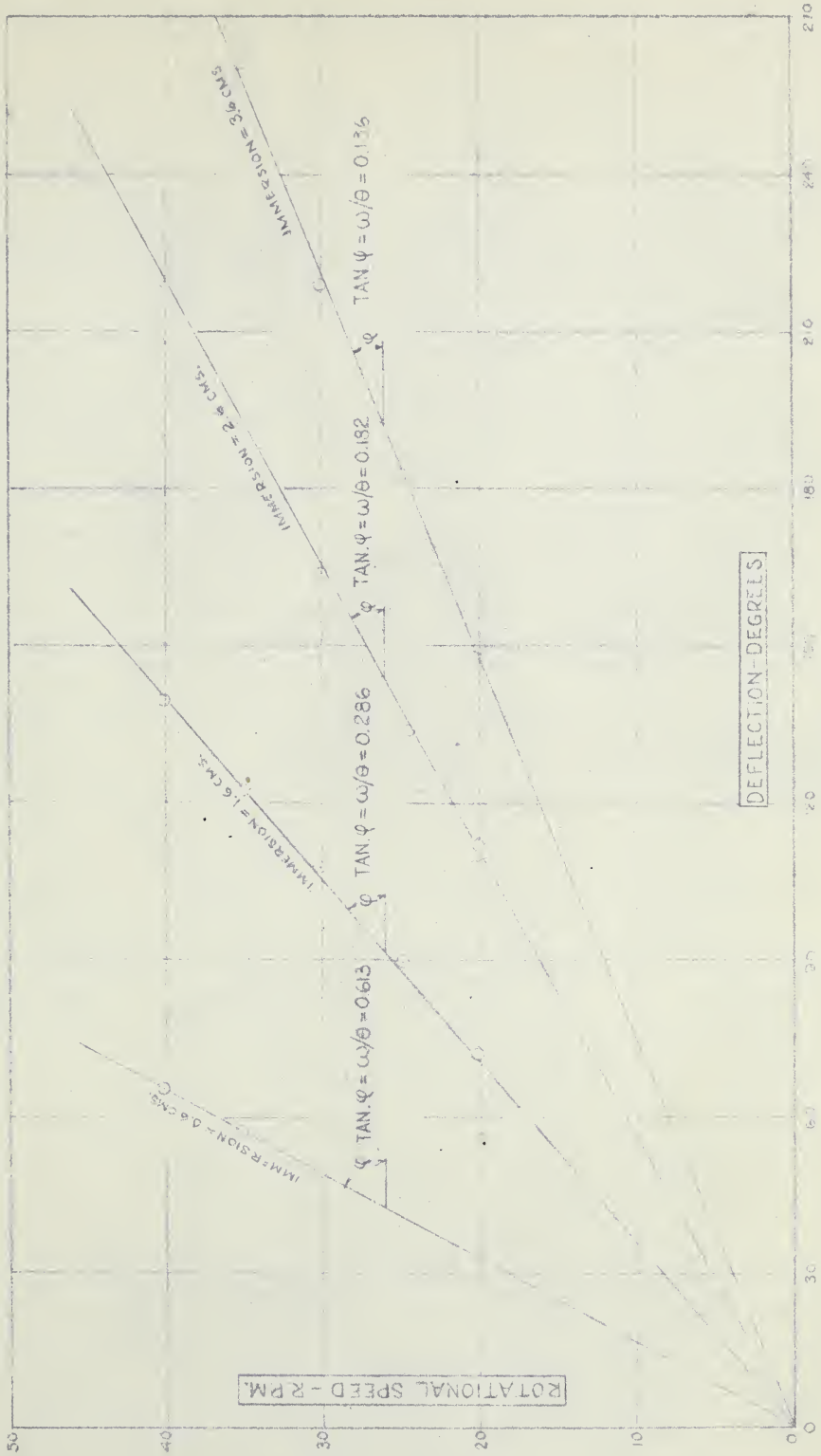


FIGURE 11

34 GAUGE TORSION WIRE CALIBRATION PLOT

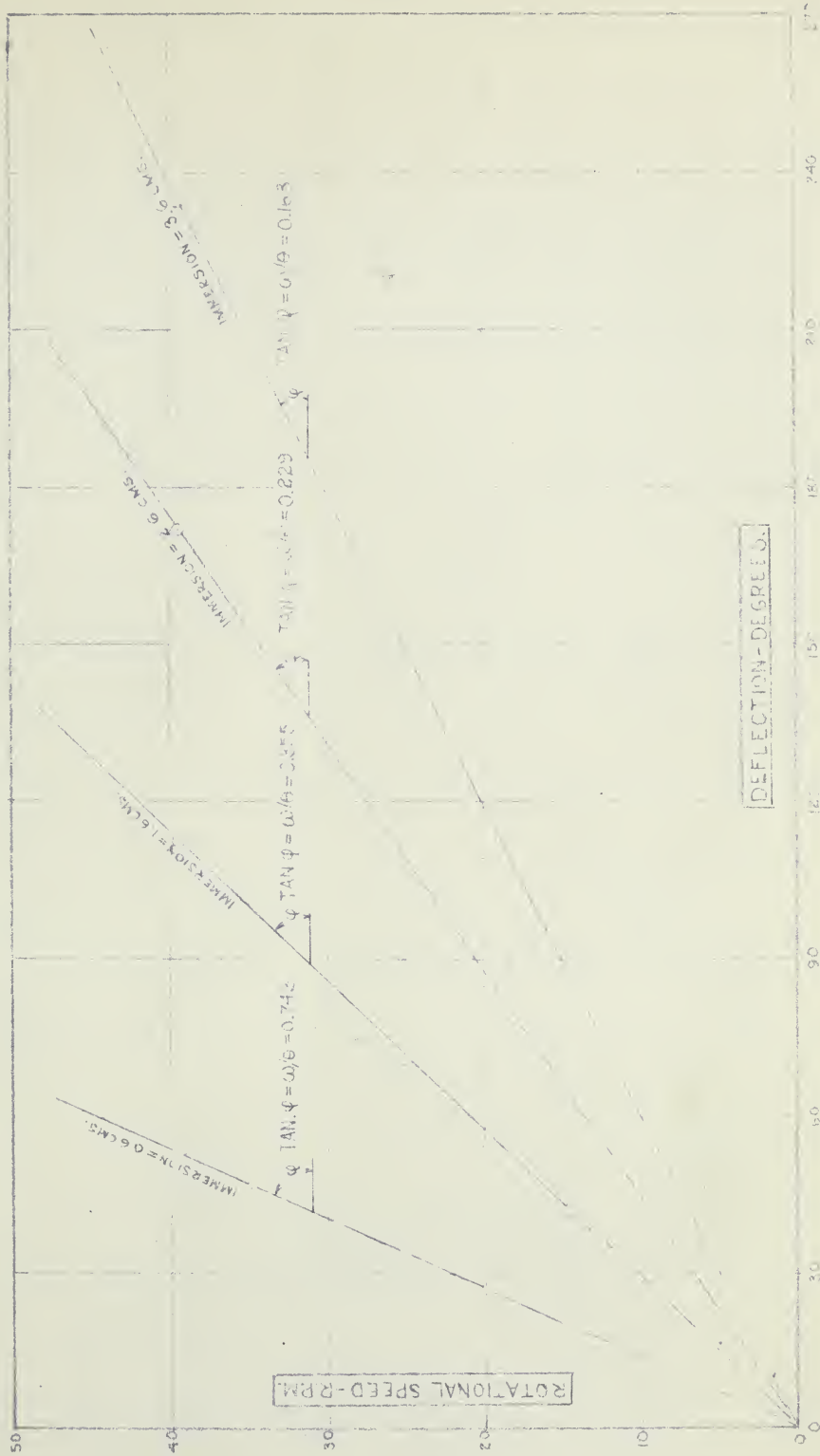


FIGURE 12

32 GAUGE TORSION WIRE CALIBRATION PLOT

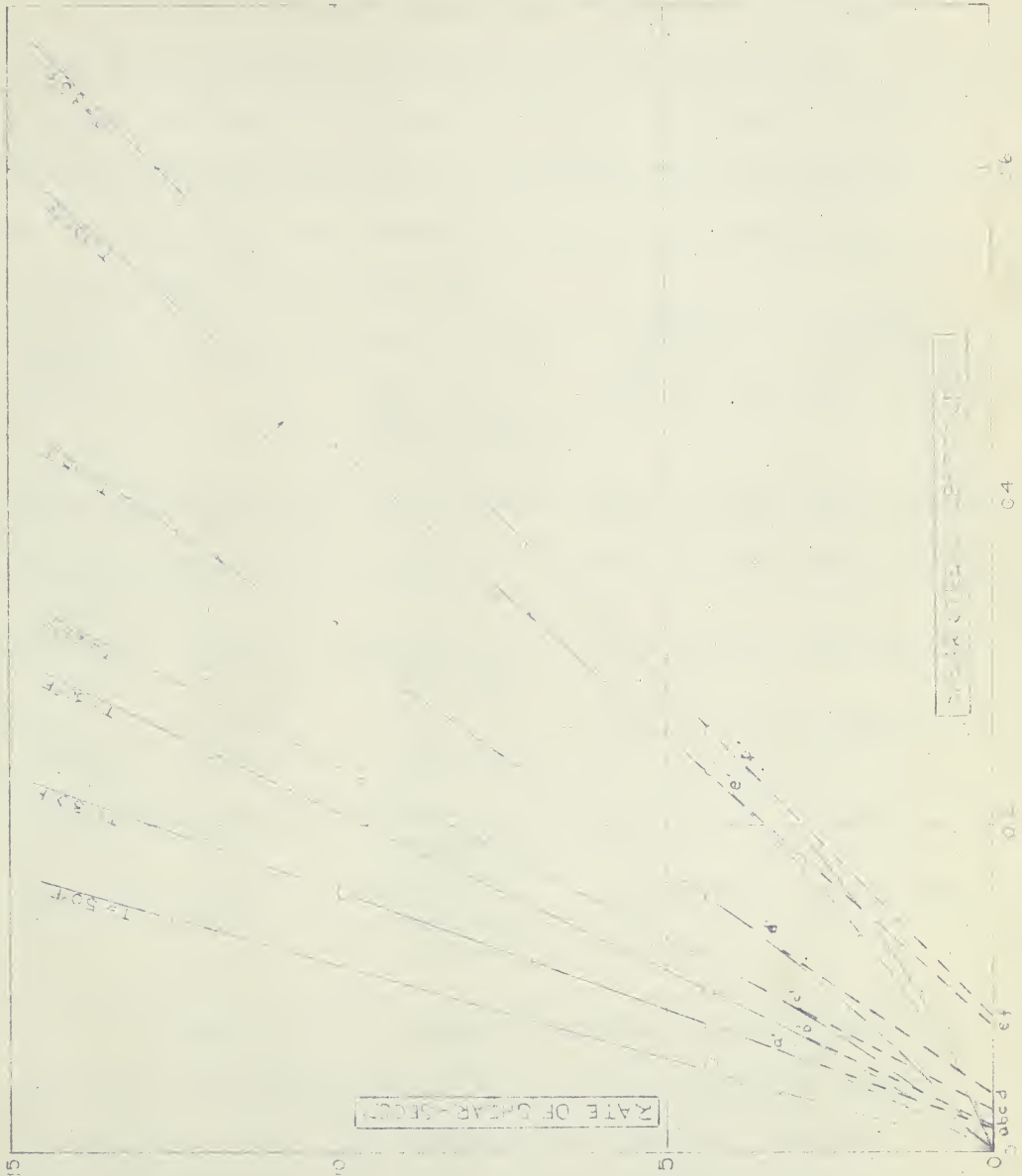


FIGURE 13
ILLUSTRATION OF THE TWO METHODS OF EXTRAPOLATING DATA

Crude Oil Tests

All the crude oil samples, with the exception of Duhamel D2 and D3, were procured and brought to the laboratory by the Petroleum and Natural Gas Conservation Board. The Duhamel D2 and D3 crude oil samples were received from Socony-Vacuum Oil Company. The following tabulation states the history of the samples prior to their arrival at the laboratory.

<u>Crude Oil</u>	<u>Well Number</u>	<u>Sampling Point</u>	<u>Date Collected</u>	<u>Date Received</u>
Redwater	-	Discharge of pump at Edmonton I.P.L. Station	Dec. 14, 1950	Dec. 14, 1950
Joseph Lake	Superior No.1	After treater	July 12, 1951	July 13, 1951
Excelsior	Imperial No.21	After separator	June 20, 1951	June 21, 1951
Leduc D2	Imperial No. 124	After separator	Feb.23, 1951	Feb. 23, 1951
Golden Spike	Imperial No. 5	After separator	July 12, 1951	July 13, 1951
Duhamel D2	Borseth No.1	After separator	Aug. 27,1951	August 28, 1951
Duhamel D3	Socony-Duhamel 17-12	After separator	Aug. 27,1951	August 28,1951.

It was necessary to convert the primary data, the rotational speeds and corresponding deflections, to rates of shear and shearing stresses respectively. The multiplication factor for converting from rotational speeds, Ω , in r.p.m., to rates of shear, $(\frac{dv}{dr})_m$, in seconds⁻¹, was determined by substituting the values of the bob and cup radii into Equation (5) and solving.

$$\begin{aligned}
 \left(\frac{dv}{dr}\right)_m &= (\Omega, \text{ r.p.m.}) \left(60 \frac{4\pi}{\frac{1}{R_b^2} - \frac{1}{R_c^2}}\right) \left(\frac{2}{R_c + R_b}\right)^2 \text{ sec.}^{-1} \quad (5) \\
 &= (\Omega, \text{ r.p.m.}) \left(60 \frac{4\pi}{\left(\frac{1}{0.992}\right)^2 - \left(\frac{1}{1.349}\right)^2}\right) \left(\frac{2}{0.992 + 1.349}\right)^2 \text{ sec.}^{-1} \\
 &= 0.332 (\Omega, \text{ r.p.m.}) \text{ sec.}^{-1} \quad (14)
 \end{aligned}$$

A knowledge of the wire constant and Equation (5) permitted the conversion from deflections to torques. The corresponding shearing stresses, F/A lbs. ft.⁻¹ sec.⁻², were then evaluated by dividing the torques by the average radius, R , ft., (to the midpoint of the annulus) and the average cylindrical area, A , ft.², (at the same point).

For the 34 gauge wire,

$$\begin{aligned}
 \text{Torque, } T &= K \theta \quad (6) \\
 &= 5.222 \times 10^{-6} \theta \text{ lbs.ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1} \\
 R &= 0.992 + \frac{0.357}{2} = 1.166 \text{ cms.} \\
 R \times A &= 1.166 \times \left(2 \times 1.166 \times 3.85\right) (0.0328)^3 \text{ ft.}^3 \\
 &= 0.00117 \text{ ft.}^3 \\
 \therefore F/A &= \frac{5.222 \times 10^{-6} \theta}{0.00117} \\
 &= 4.46 \times 10^{-3} \theta \text{ lbs. ft.}^{-1} \text{ sec.}^{-2} \quad (15)
 \end{aligned}$$

This was the shearing stress at 3.85 cms. corrected depth of immersion.

In some cases, where a lesser depth of immersion was employed to prevent overranging of the torsion wire, the conversion factor was obtained by multiplying the one at 3.85 cm. depth of immersion by the ratio of the corrected depths.

The 32 gauge torsion wire was not used in any tests because it was thought better to decrease the depth of immersion when danger of overranging was present than to switch wires in mid-test. If it had been used the conversion factor would be evaluated as above except that the 32 gauge wire constant would be substituted in place of the 34 gauge wire constant.

The results of these data, shown in plotted form, are included with the discussion of each crude oil to facilitate reading.

Note:-

The conversion constants, Equations 14 and 15, were checked by evaluating the absolute viscosity of the 149.8 centipoise (0.1007 lbs./ft.sec.) standard oil from data plotted in Figure 11. The deflection at 33 r.p.m. rotational speed with 3.6 cms. actual depth of immersion is 243 degrees.

$$\begin{aligned}\text{Then } \left(\frac{dv}{dr}\right)_m &= 0.333 (33 \text{ r.p.m.}) \text{ secs.}^{-1} \\ &= 11 \text{ secs.}^{-1}\end{aligned}$$

$$\begin{aligned}F/A &= 4.46 \times 10^{-3} (243) \text{ lbs. ft.}^{-1} \text{ sec.}^{-2} \\ &= 1.084 \text{ lbs. ft.}^{-1} \text{ sec.}^{-2}\end{aligned}$$

$$\begin{aligned}\mu &= F/A / \left(\frac{dv}{dr}\right)_m \\ &= \frac{1.084}{11.0} \\ &= 0.985 \text{ lbs./ft. sec.}\end{aligned}$$

$$\begin{aligned}\text{Percent error} &= \frac{1.007 - 0.985}{1.007} \times 100\% \\ &= 2\%.\end{aligned}$$

DISCUSSION OF RESULTS

End Effect Correction

The data listed in Tables I, II (A) and III(A) and plotted in Figures 8, 9, and 10 are considered very reliable in spite of the fact that it was difficult to reproduce constant rotational speeds with an error of less than 1%. Each of the seventeen curves is linear, passes through all the points, and intersects the depth of immersion axis at the same point. It is difficult to arrive at a percentage error in the end effect correction mathematically. It is safe to assume though that, since all the curves intersect at a common point, the correction is accurate. The results obtained from testing the two 34 gauge and the 32 gauge wires with corresponding 149.8 centipoise and 310.3 centipoise standard oils have proved the theoretical statement that the end effect correction is independent of the viscosity of the liquid but depends only on the dimensions of the instrument.

Torsion Wire Calibration

The curves, Figures 11 and 12, plotted from data in Tables II (A) and III (A) for the 34 gauge wire and the 32 gauge wire respectively, are all linear and intersect at the origin. The calibration constants at four depths of immersion for both wires were calculated from the slopes of the lines. Since the constant for each

wire was desired to be independent of the depth of immersion an average value was arrived at by attaching varying significance to the values obtained at the different depths of immersion. An error of 0.05 cms. in reading the depth of immersion was assumed. Then the percentage errors in reading the 0.35, 1.85, 2.85, and 3.85 cm. corrected depths of immersion were 6%, 3%, 2%, and 1% respectively. Therefore an arbitrary weight of 4 was attached to the value at 3.85 cms. immersion and the comparative weights attached to the 2.85, 1.85 and 0.35 cms. immersions were 3, 2, and 1 respectively. Data in Table II (B) show that the maximum deviation of an individual K value from the weighted average K value is approximately 1%. The value for the 34 gauge torsion wire calibration constant is therefore probably accurate to within 1%.

Date for the 32 gauge wire, Table III (B), employing the same weighting technique shows a maximum deviation of over 2%. It is the K value at the 0.85 cm. corrected depth of immersion though, to which the least weight is attached, that shows this maximum deviation. Therefore the weighted average K value for the 32 gauge wire is probably accurate to within 2%.

Method of Extrapolating Shear Stress - Rate of Shear Data

When the shearing stress data, obtained from testing the crude oils at higher temperatures, were plotted against the corresponding rates of shear in the 4 to 15 sec.⁻¹ range the curves were linear and their extrapolations passed through the origin indicating Newtonian behavior. At lower temperatures, however, the continuation of the

straight line portion of the curves did not intersect at the origin; that is, the oils no longer behaved as Newtonian liquids.

Two extrapolations from the 4 sec.^{-1} to the zero sec.^{-1} rates of shear were possible. One was to assume that the oil behaved as a Bingham plastic; that is, it possessed a yield value at lower temperatures. In such a case the extrapolation would involve the continuation of the straight like portion until it intersected the zero rate of shear axis. This method of extrapolation is indicated in Figure 13 by the dotted lines a'a, b'b, c'c, c'd, e'e, and f'f. The yield values at each temperature are a, b, c, d, e, and f lbs. $\text{ft.}^{-1} \text{ sec.}^{-2}$. The apparent coefficient is then determined by means of Equation (2). This method of interpretation may be legitimate when one is concerned with the viscous properties at high rates of shear. At low rates of shear, however, it is wrong to assume a yield value because, as mentioned in the theory, the curve is seldom a straight line. Due to slippage the line begins to curve toward the origin as the zero rate of shear is approached. Therefore, without low rates of shear data, the yield value cannot be determined accurately.

The second method of interpreting the data at low rates of shear was to extrapolate the straight line portions to the origin by smooth curves as indicated in Figure 13. This method appears to be more consistent with the data. The shearing stresses observed at the lowest ratio of shear, when plotted, were often to the left of the straight line portion thereby indicating a tendency to converge to the origin.

Crude Oil Tests

The results obtained from testing each crude oil sample are discussed individually. The first oil tested was Redwater crude so it is discussed first.

Redwater Crude Oil

The primary data (rotational speeds and corresponding deflections at each testing temperature) obtained from the testing of a Redwater crude oil sample, precooled to 10°F, are listed in columns 2 and 3 of Table IV. These data were converted to shear stresses and rates of shear as outlined previously and are shown in columns 4 and 5 respectively. These shear stress - rate of shear data at the different testing temperatures are shown plotted in Figure 14.

Observation of the plot reveals that the oil ceases to behave as a non-Newtonian liquid (i.e., the straight line extrapolation does not pass through the origin) when the testing temperature exceeds 35°F. The shear stress - rate of shear plots at 40°F and 50°F both pass through the origin indicating Newtonian behavior. The transition from non-Newtonian to Newtonian behavior, therefore, takes place in the 35°F. to 40°F. range. Since wax deposition was observed at temperatures below 35°F. during testing it is probable that this range also includes the "wax point". In fact, it is likely that the transition from Newtonian to non-Newtonian behavior occurs at the wax point.

The second sample of the same crude oil, prewarmed to 70°F. to test the effect of previous thermal treatment, yielded data listed in columns 1, 2, and 3 of Table V. These data were converted to shearing stresses and rates of shear as before and plotted in Figure 15.

The results of this test show that the transition from Newtonian to non-Newtonian behavior took place between 50°F and 60°F. They also show that the shearing stresses are much larger than those of the first tests at the same rates of shear. This difference is clearly not the result of non-attainment of temperature equilibrium because 15 minutes were allowed in proceeding from one temperature level to the next, and the sample was maintained at each temperature for a further 15 minutes before testing. This length of time allowed the circulation of approximately 20 U.S. gallons of cooling liquid through the MacMichael bath. The only possible explanation is therefore that these higher shearing stresses resulted from the different thermal treatment.

For a complete verification of the variation in rheological properties with varying thermal treatment, however, data in Tables VI to IX inclusive were obtained by the testing of four more samples. Two samples were prewarmed as before, one was precooled, and the fourth was maintained at 50°F. for 6 hours and then decanted.

Test No. 3, on a sample prewarmed to 70°F, yielded data listed in Table VI and plotted in Figure 16. The shear stress - rate of shear diagram, Figure 16, is similar to Figure 15. The slight deviation is probably due to the inability of reproducing thermal treatments exactly. The results of this test indicate the Newtonian to non-Newtonian transition took place between 40°F. and 50°F.

The data obtained from Test No. 4, on a sample precooled to 5°F, are tabulated in Table VII and plotted in Figure 17. The results indicate that the transition from non-Newtonian to Newtonian behavior took place in the 37.5°F. to 40°F. temperature range.

Test No. 5, on a sample prewarmed to 70°F., yielded data listed in Table VIII and plotted in Figure 18. The results show that the transition occurred at a temperature above 35°F. This test would be more conclusive if more data had been obtained at the lower temperatures.

Data obtained from the sixth test, cooled to 5°F. and maintained at that temperature for 6 hours in an effort to take a portion of the wax out of suspension and deposit it on the walls of the containing flask, are shown tabulated in Table IX and plotted in Figure 19. The stress - shear diagram indicates the non-Newtonian to Newtonian transition occurred at a temperature above 49°F. Otherwise the diagram approximates those of the previous precooled samples.

The apparent viscosity data, derived from the plotted data of each test, at four rates of shear for each temperature are tabulated in Table XXII. Figure 20 shows these data plotted and averaged by drawing best fit curves for four rates of shear through the points. The data resulting from Test No. 2 and from Test No. 6 are higher than those of the other corresponding prewarmed and precooled sample tests.

The higher data of the sixth test are probably the result of the more extreme thermal treatment that the sample was subjected to. The scattering of the remaining data is likely due to the variation in thermal treatment. It is noted that the data from individual tests is quite uniform. The effect of previous thermal treatment is most pronounced at lower temperatures. At 100°F. the apparent viscosities of the prewarmed crude are about three times those of the precooled crude. At 50°F. the apparent viscosities of the two samples are the same. The transition from Newtonian to non-Newtonian behavior is 42°F. in the case of the precooled crude oil and 50°F. in the case of the prewarmed crude. Wax deposition was generally observed below 35°F. when precooled crude was tested and below 30°F. when prewarmed crude was tested. It is likely though that appreciable quantities of wax had deposited before they were observed visually. Therefore it is conceivable that the wax point was at 42°F. for precooled crude and 50°F. for prewarmed crude.

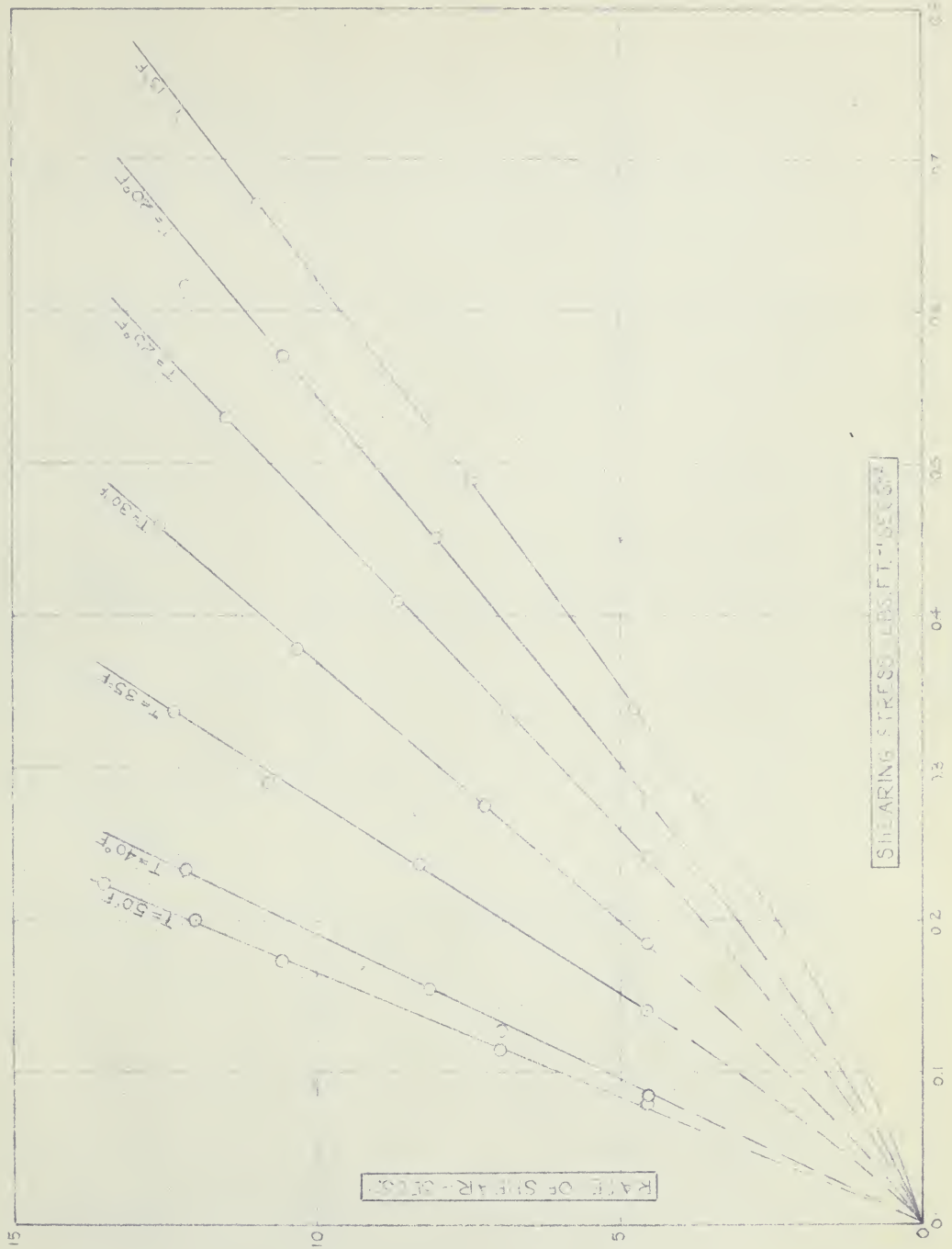


FIGURE 14

TEST NO. 1: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL PRECOOLED TO 10° F.

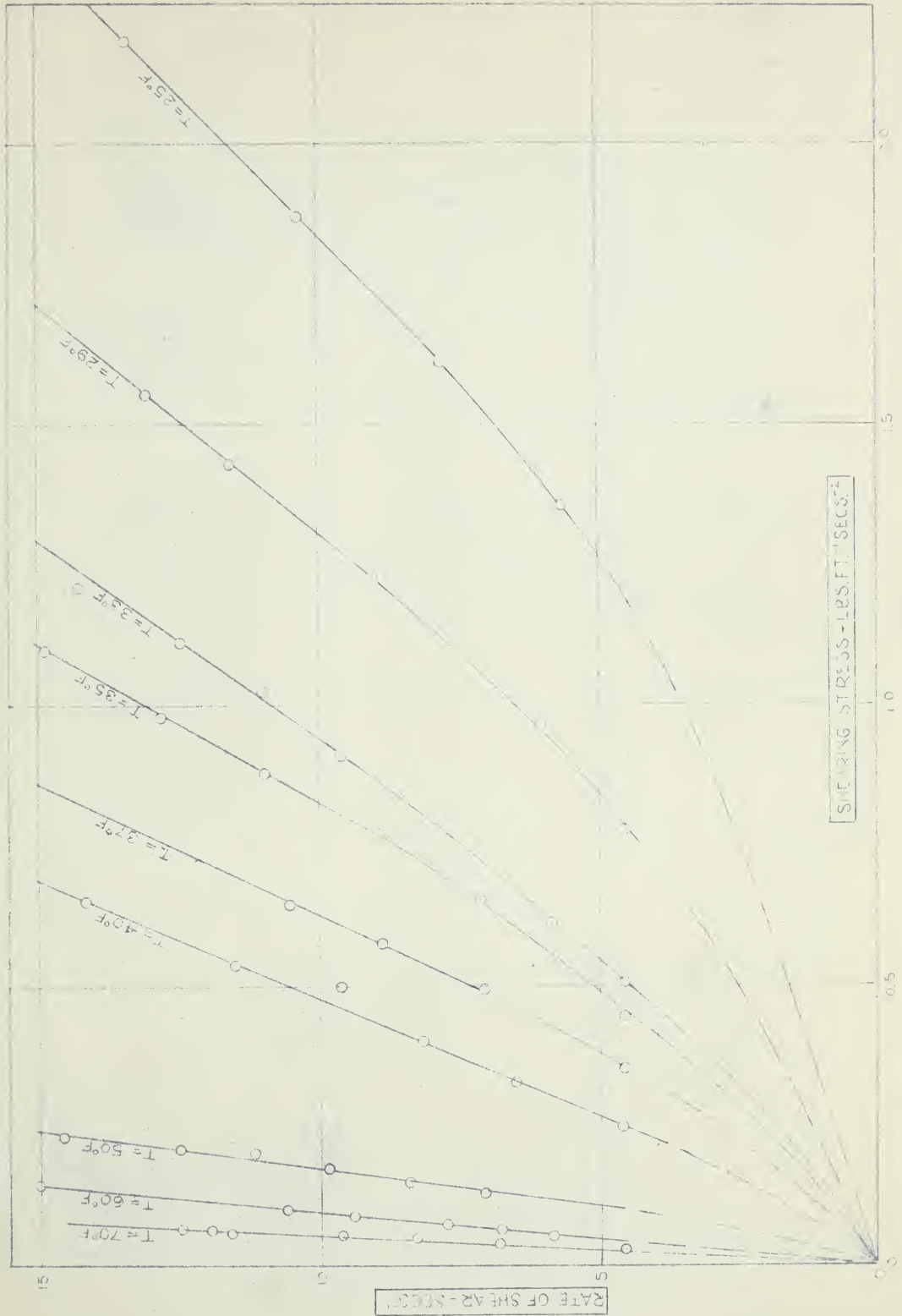


FIGURE 15

TEST NO. 2: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL PREWARMED TO 70°F .

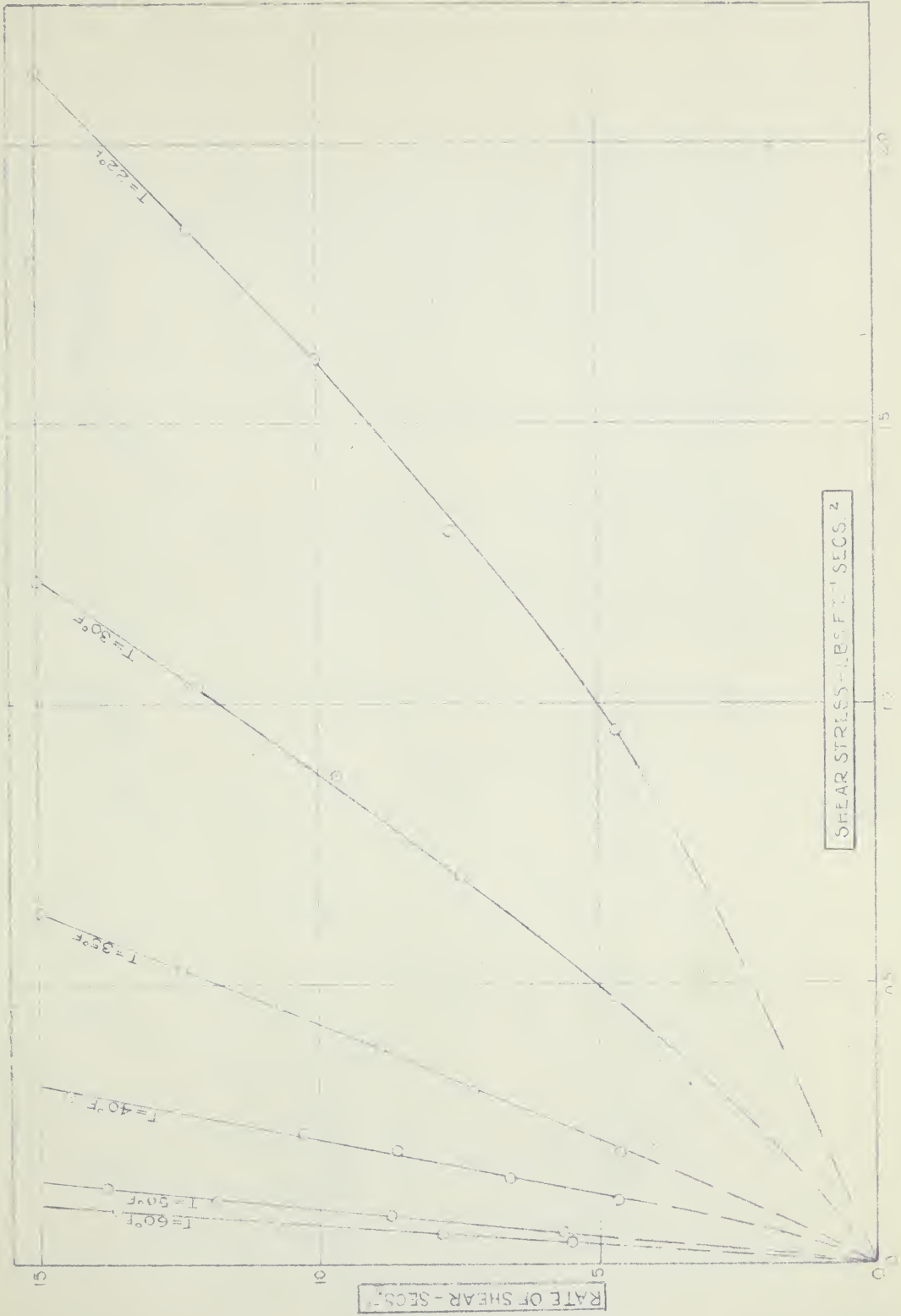


FIGURE 16

TEST NO 3: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL PREWARMED TO 70°F.

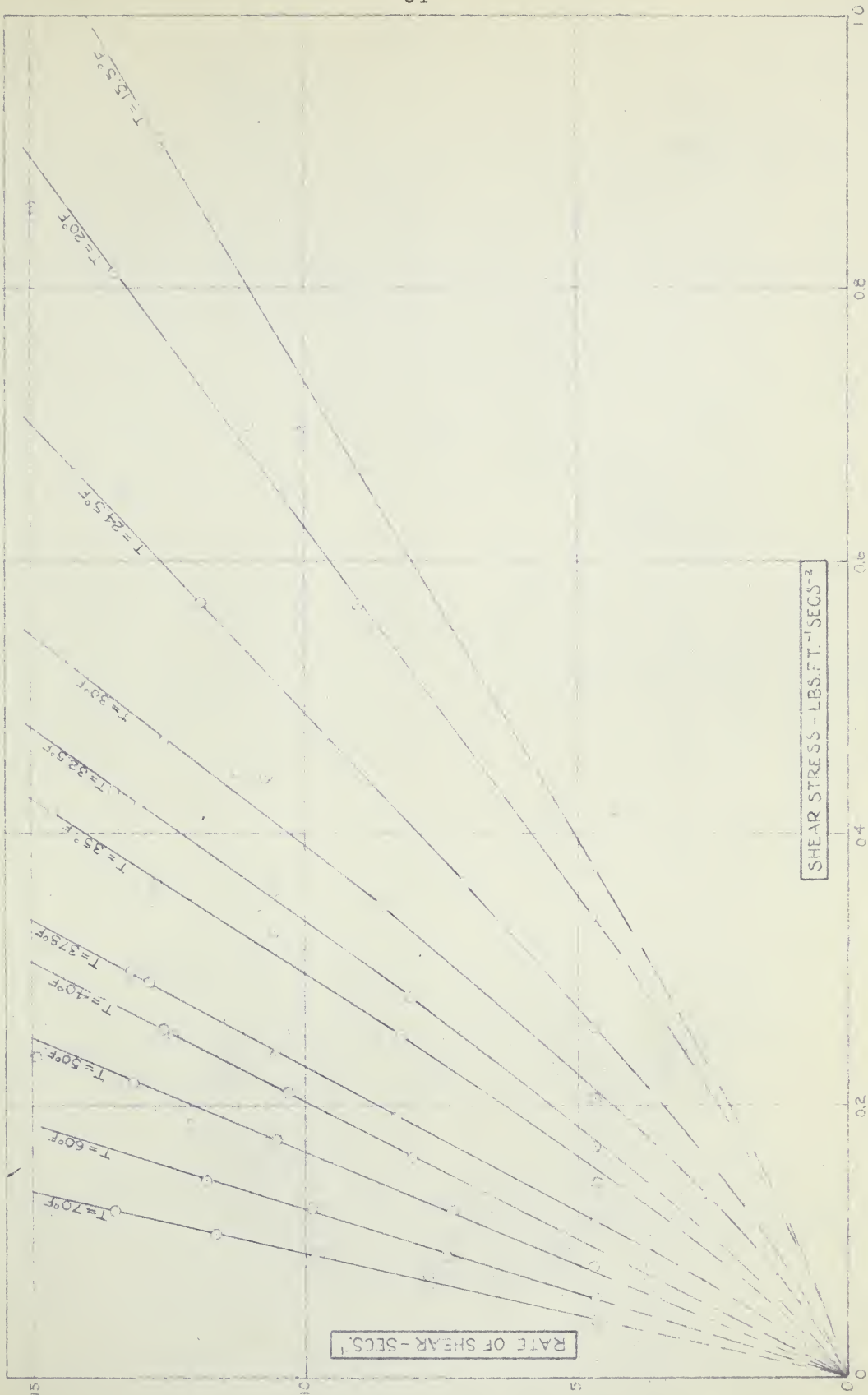


FIGURE 17

TEST NO. 4: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL PRECOOLED TO 5°F.

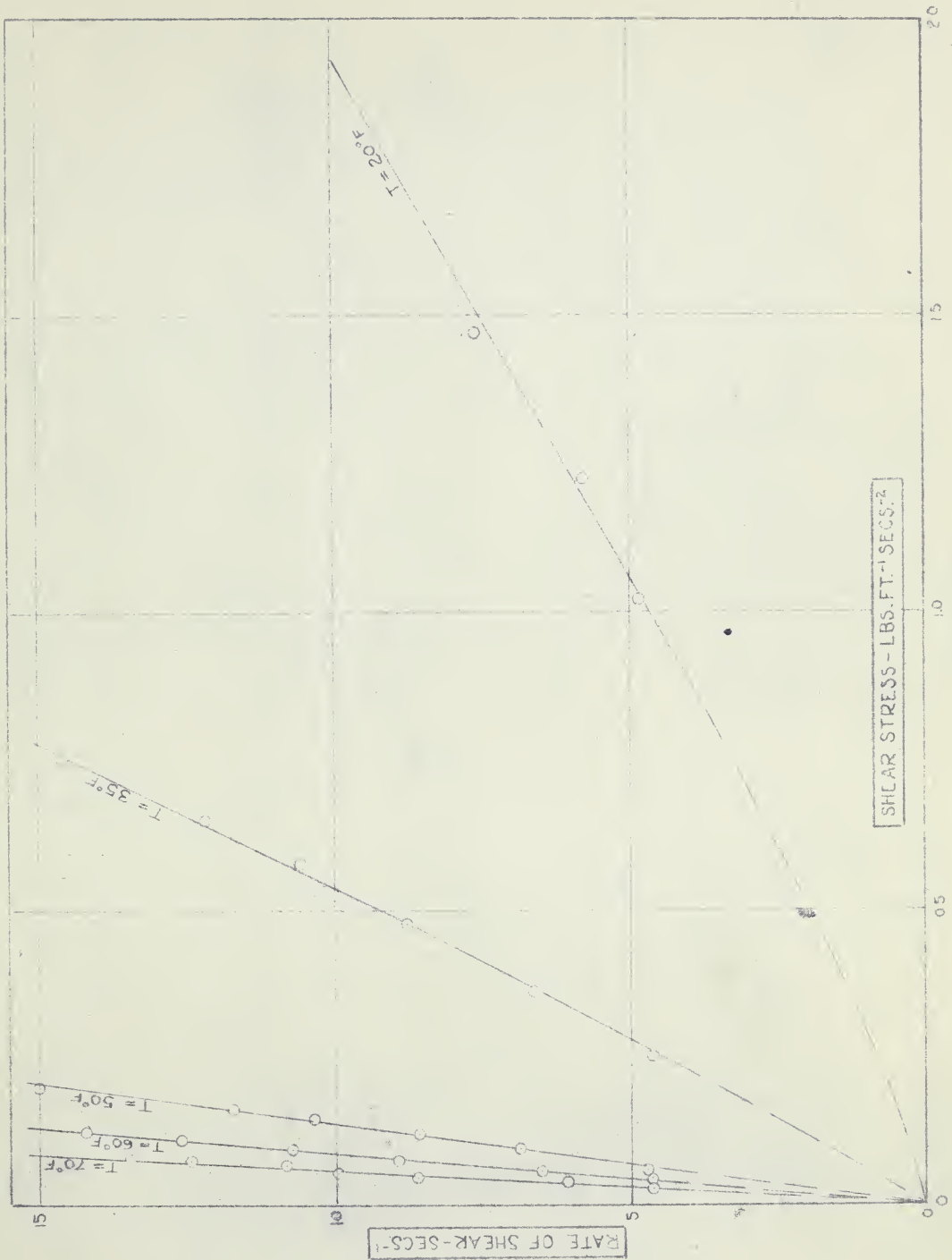


FIGURE 18

TEST NO 5: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL PREWARMED TO 70°F.

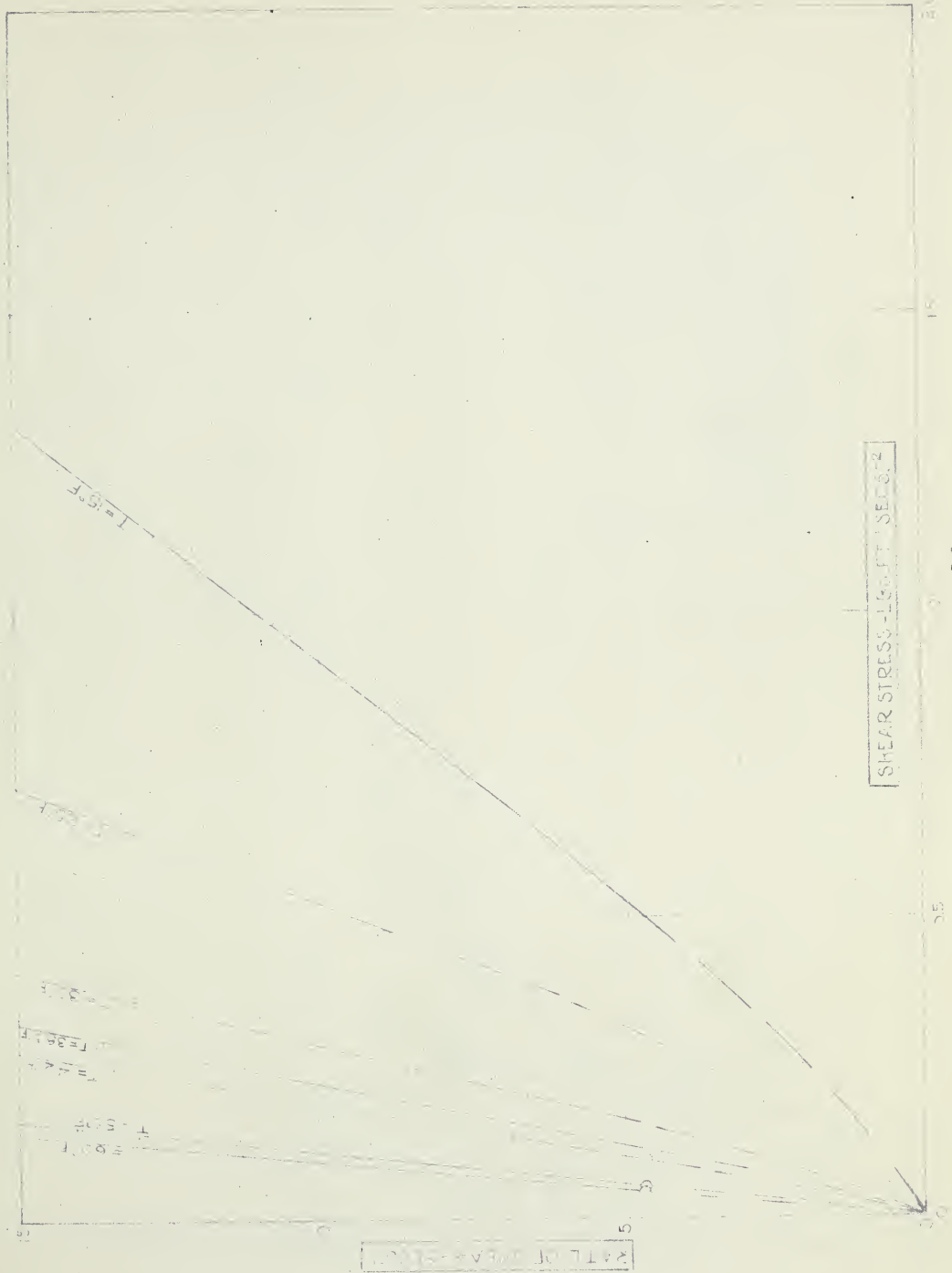


FIGURE 19

TEST NO 6: RHEOLOGICAL PROPERTIES OF REDWATER CRUDE OIL MAINTAINED AT 5°F. FOR 6 HRS.

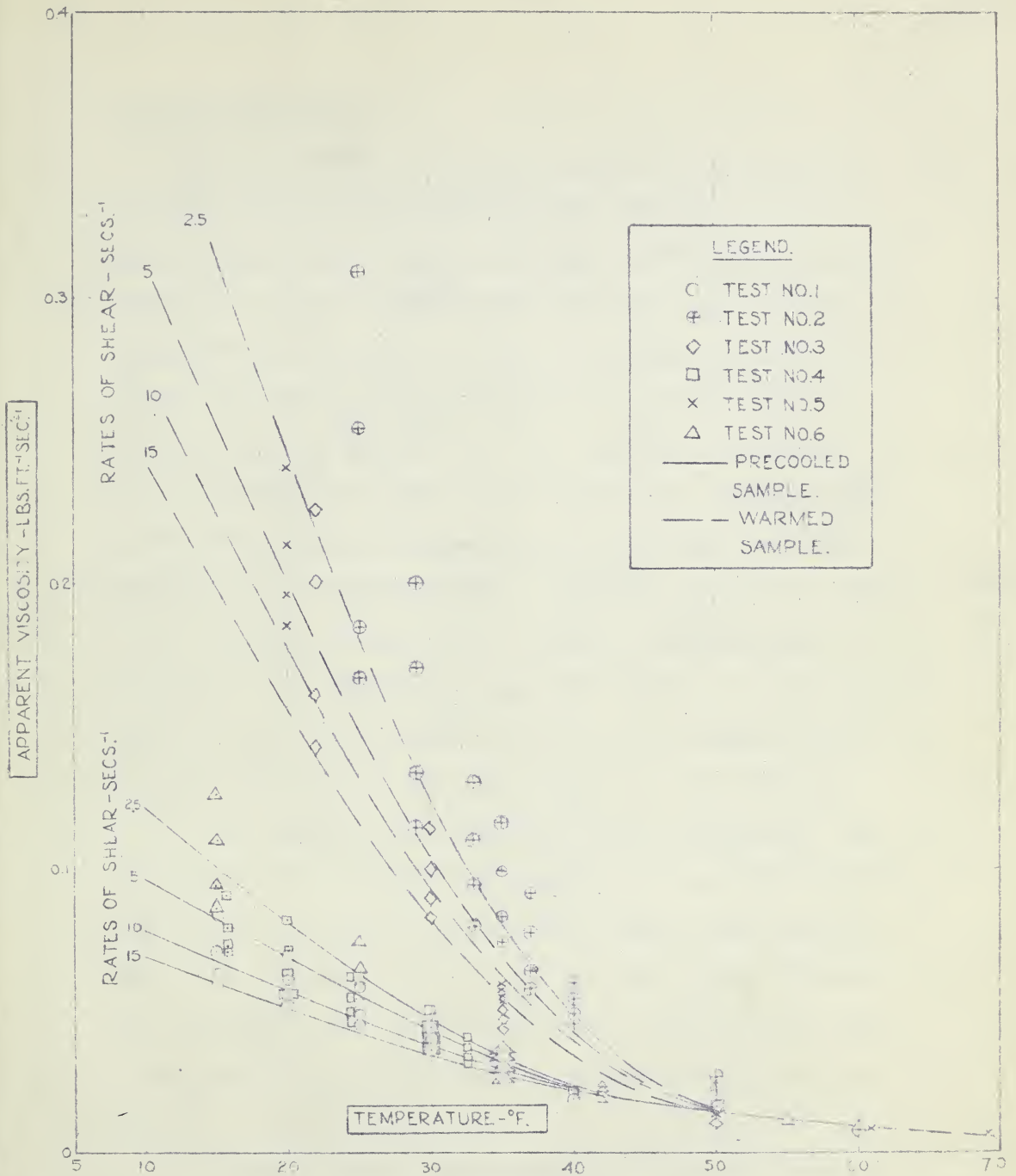


FIGURE 20

APPARENT VISCOSITIES OF REDWATER CRUDE OILS PRECOOLED TO 5°F. AND PREWARMED TO 70°F.

Joseph Lake Crude Oil

The primary data, (rotational speeds and corresponding deflections at the different temperatures) obtained by testing a sample of Joseph Lake crude oil, prewarmed to 70°F, are tabulated in columns 1, 2, and 3 of Table X. These data were then converted to shearing stresses and rates of shear as before and are listed in Columns 4 and 5 of the same table. The plot of these data at each temperature is shown in Figure 21. The Newtonian to non-Newtonian transition is seen to occur above 49°F. The data taken at 30°F. do not appear reliable because the best-fit curve does not include all the points.

The second test, run on a sample of the same crude, precooled to 5°F., yielded data listed in Columns 1, 2, and 3 of Table XI which were converted to those listed in Columns 4 and 5. These converted data were plotted in Figure 22.

Non-uniformity of results is evident on this plot. The shear-stress curve at 26°F, which should lie to the left of the 20°F. curve, cuts it at 8 sec.⁻¹ rate of shear. Below 8 sec.⁻¹ rate of shear it is positioned to the right of the 20°F. curve. Furthermore, the 29.5°F. curve, which should be in a position to the left of both the 20°F. and 26°F. curves, is positioned to the right of both.

Obviously some of these results are incorrect. During testing of the crude oil sample considerable wax deposition was noted

Low-Pressure Curve Oil

The primary data, (rotational speeds and corresponding

delivered at the different temperatures) obtained by testing a

sample of Low-Pressure Curve Oil, presented in Table I, and listed in

columns 1, 2, and 3 of Table I. These data were also converted to

shear stress and rate of shear as before and are listed in

columns 4 and 5 of the same table. The plot of these data is

shown in Figure 11. The deviation from linearity is

Newtonian transition is seen to occur above 1000. The same behavior

at 3000. do not appear reliable because the test-life curve was

not included all the points.

The second test, run on a sample of the same oil,

presented in Table II, listed data listed in columns 1, 2, and 3 of

Table II which were converted to shear stress and rate of shear as

before and are listed in Figure 12.

Non-linearity of plotting is evident in this plot. The

shear stress curve at 3000, which would be the left of the 3000.

curve, was at 3 sec. rate of shear. Below 3 sec. rate of

shear it is positioned to the right of the 3000. curve. Below

more, the 3000. curve, which would be the left of the 3000.

of both the 3000. and 3000. curves, is positioned to the right of

both.

Probably some of these results are incorrect. During

testing of the curve oil sample considerable gas evolution was noted.

at temperatures below 35°F. It is possible that changes in orientation of the wax crystals occurred during the test causing varying distortion of the geometry of the system and resulting in erratic data. It was therefore necessary to discard the data which were thought to be inconsistent. The 20°F. and 15.5°F. curves seem reliable in that they are positioned uniformly in relation to one another; that is, the 20°F. curve is to the left of the 15.5°F. and is of a greater slope, as it should be. This relationship is not conformed with in either respect in the case of the 26°F. and 29.5°F. curves. The 29.5°F. curve is not positioned to the left of the 26°F. curve nor is it of a greater slope. This inconsistency resulted in the decision to discard the data at 26°F. and 29.5°F.

The apparent viscosity data, derived from the plotted data as before, are tabulated in Table XXII and plotted in Figure 23. This plot indicates only slightly larger apparent viscosities for prewarmed crudes than for precooled crudes. The transition from Newtonian to non-Newtonian behavior is seen to occur at 65°F. in the case of prewarmed crude and at 53°F. in the case of the precooled crude. These then, are probably the wax points of the corresponding samples.



FIGURE 21

TEST NO 1: RHEOLOGICAL PROPERTIES OF JOSEPH LAKE CRUDE OIL PREWARMED TO 70°F.

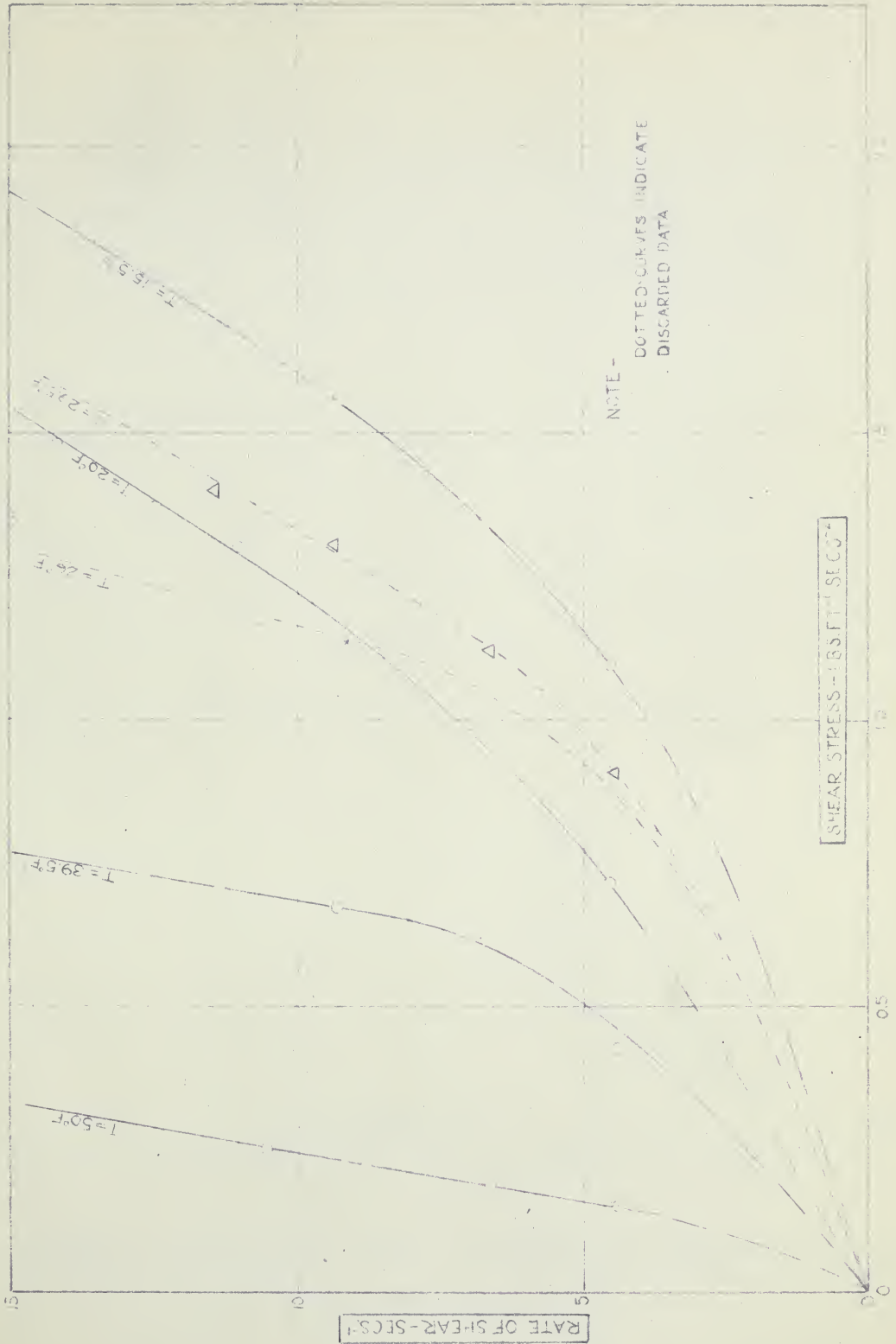


FIGURE 22

TEST NO.2: RHEOLOGICAL PROPERTIES OF JOSEPH LAKE CRUDE OIL PRECOOLED TO 5 °F.

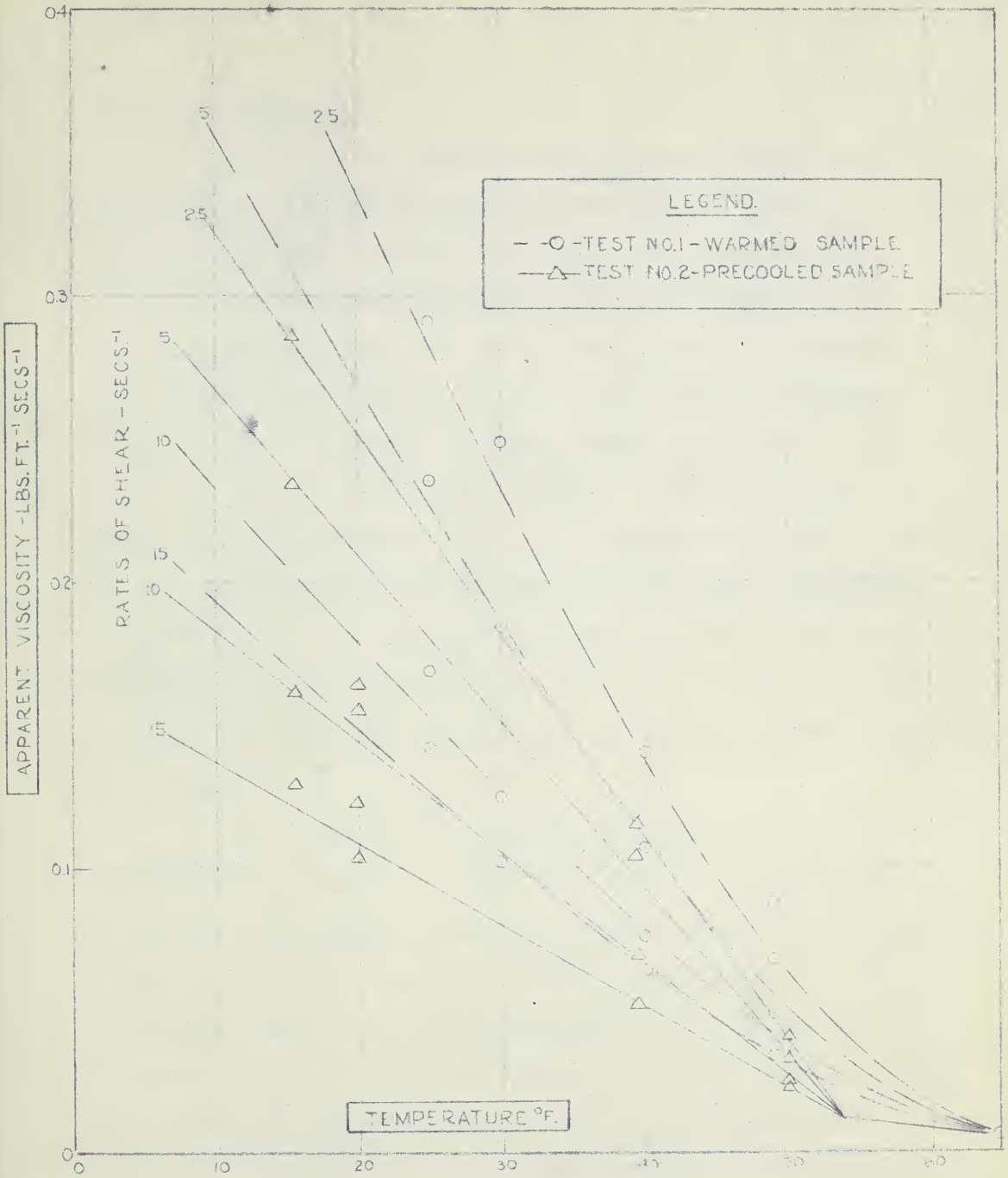


FIGURE 23

APPARENT VISCOSITIES OF JOSEPH LAKE CRUDE OIL PREWARMED TO 70°F.
 and PRECOOLED TO 5°F.

Excelsior D2 Crude Oil

A sample of Excelsior D2 crude oil, when precooled to 10°F. and tested at the successively increasing temperatures indicated in Column 1 of Table XII, yielded the rotational speed and deflection data listed in Columns 2 and 3 respectively of the same table. These data were then converted to shearing stress and rate of shear data listed in Columns 4 and 5. The plot of these data is shown in Figure 24. The non-Newtonian to Newtonian transition apparently occurred in the 40°F. to 50°F. temperature range. The shear - stress curve at each temperature appears reliable.

The second test on the same crude oil, subjected to warming to 60°F. prior to testing, resulted in data tabulated in Table XIII and plotted in Figure 25. This plot also seems reliable and indicates that the transition in behavior occurred in the 30°F. to 40°F. temperature range.

The derived apparent viscosity - temperature data, listed in Table XXII and plotted in Figure 26, show that, at temperatures below 200°F., the apparent viscosities of the prewarmed crude oil are higher at all rates of shear than those of the precooled crude oil. Above 30°F, however, the apparent viscosities of the precooled sample are higher. If the shear-stress data had not appeared reliable this reversal in difference between apparent viscosities would be questioned. However, since all the data are assumed to be significant this reversal in difference is judged to be an actual occurrence.

The extrapolations between 50°F. and 60°F. in Figure 26 are rather lengthy so the difference in apparent viscosities at 60°F. could easily be less than that indicated.

The change from Newtonian to non-Newtonian behavior is shown to have occurred at 39 F. for the prewarmed crude oil and 49°F. for the precooled crude oil. No appreciable wax deposition was noted at any temperature during testing of either sample.

The extrapolations between 50°F. and 63°F. in Figure 26 are rather lengthy as the difference in apparent viscosity at 50°F. could easily be less than that indicated.

The change from Newtonian to non-Newtonian behavior is shown to have occurred at 39°F. for the pressure range 0.1 to 1000 psi. For the pressures 0.1 to 1000 psi. No appreciable change was observed at any temperature during testing of either sample.

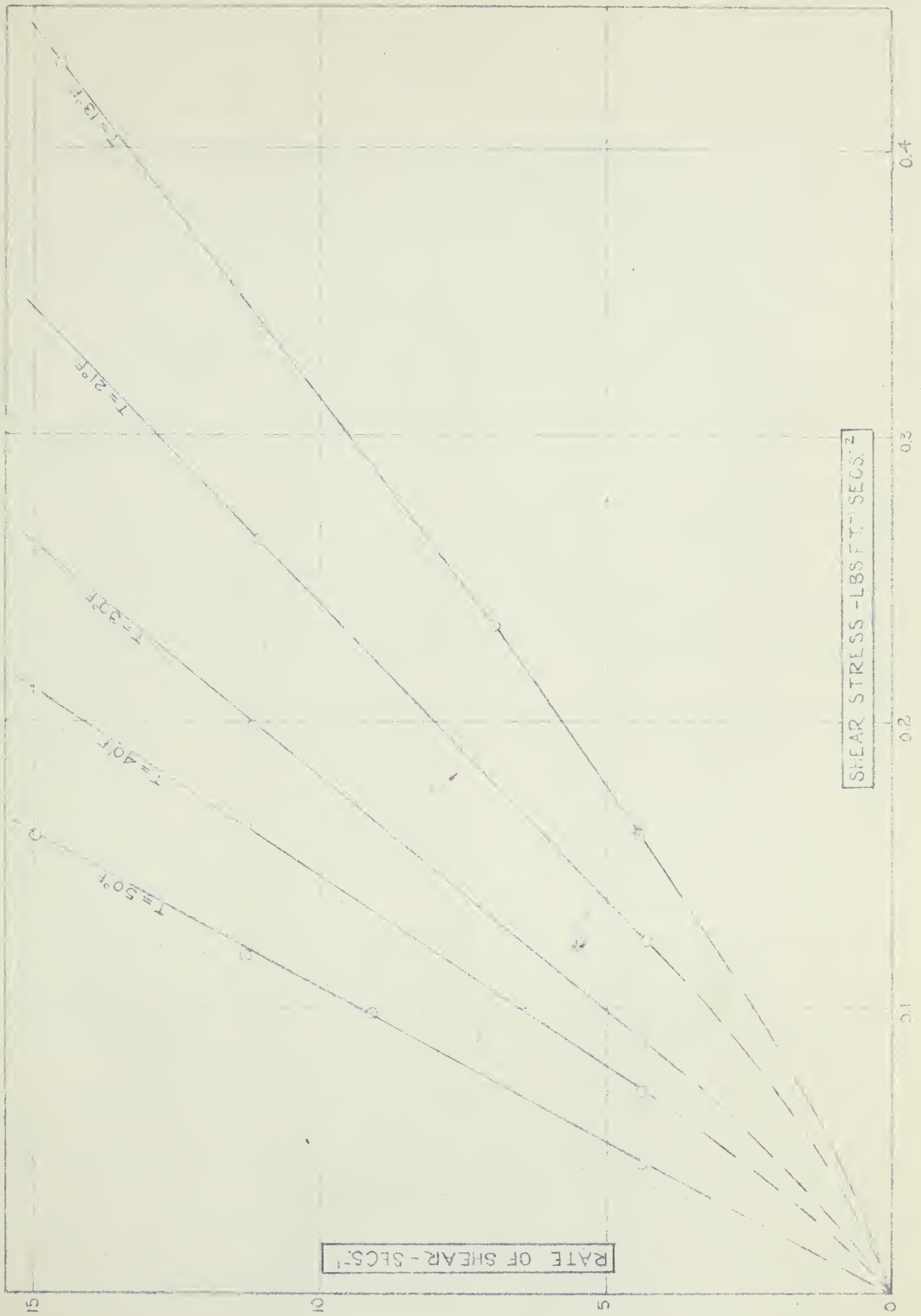


FIGURE 24

TEST NO 1: RHEOLOGICAL PROPERTIES OF EXCELSIOR D2 CRUDE OIL PRECOOLED TO 10°F .

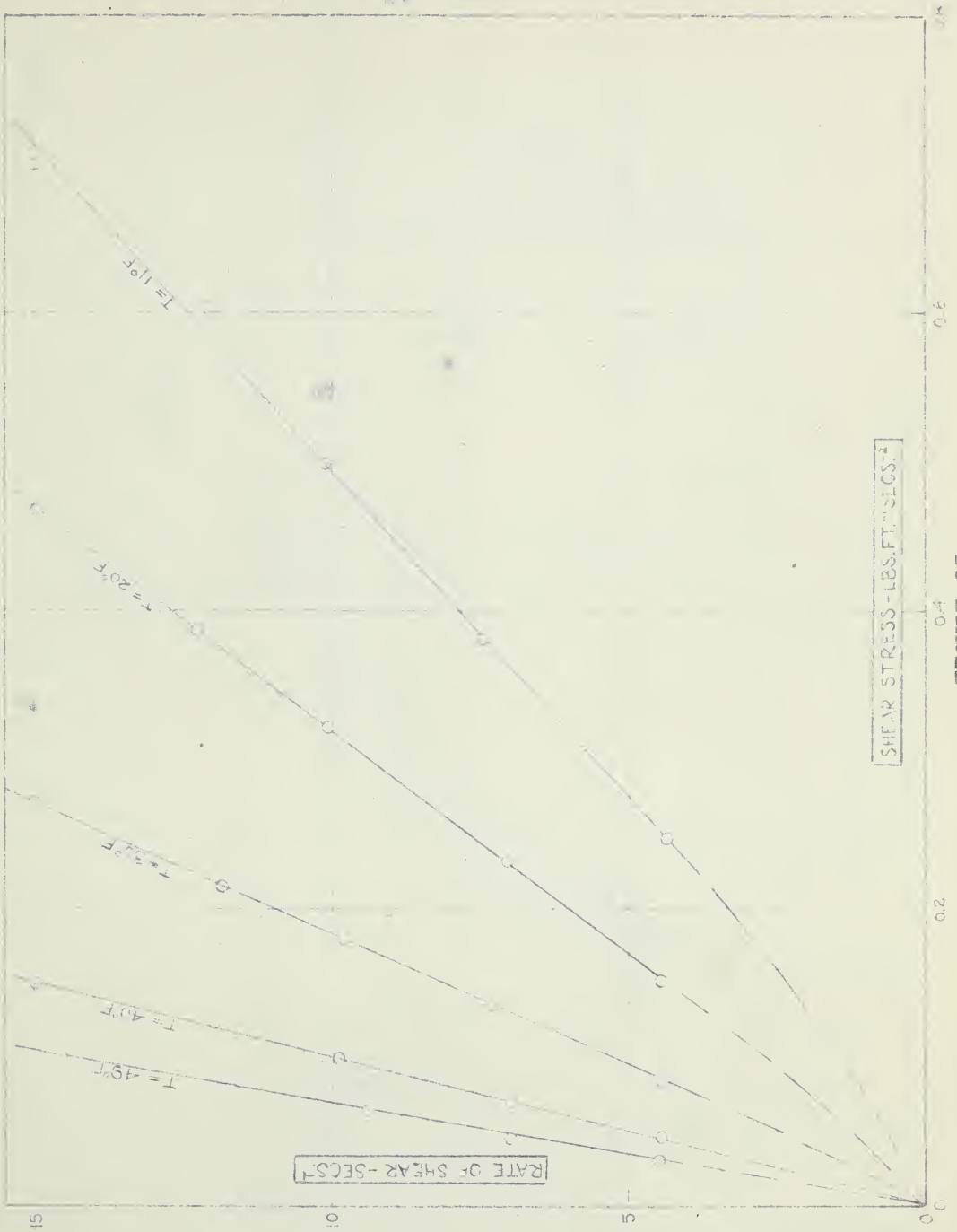


FIGURE 25
TEST NO.2: RHEOLOGICAL PROPERTIES OF EXCELSIOR D2 CRUDE OIL PREWARMED TO 60°F.

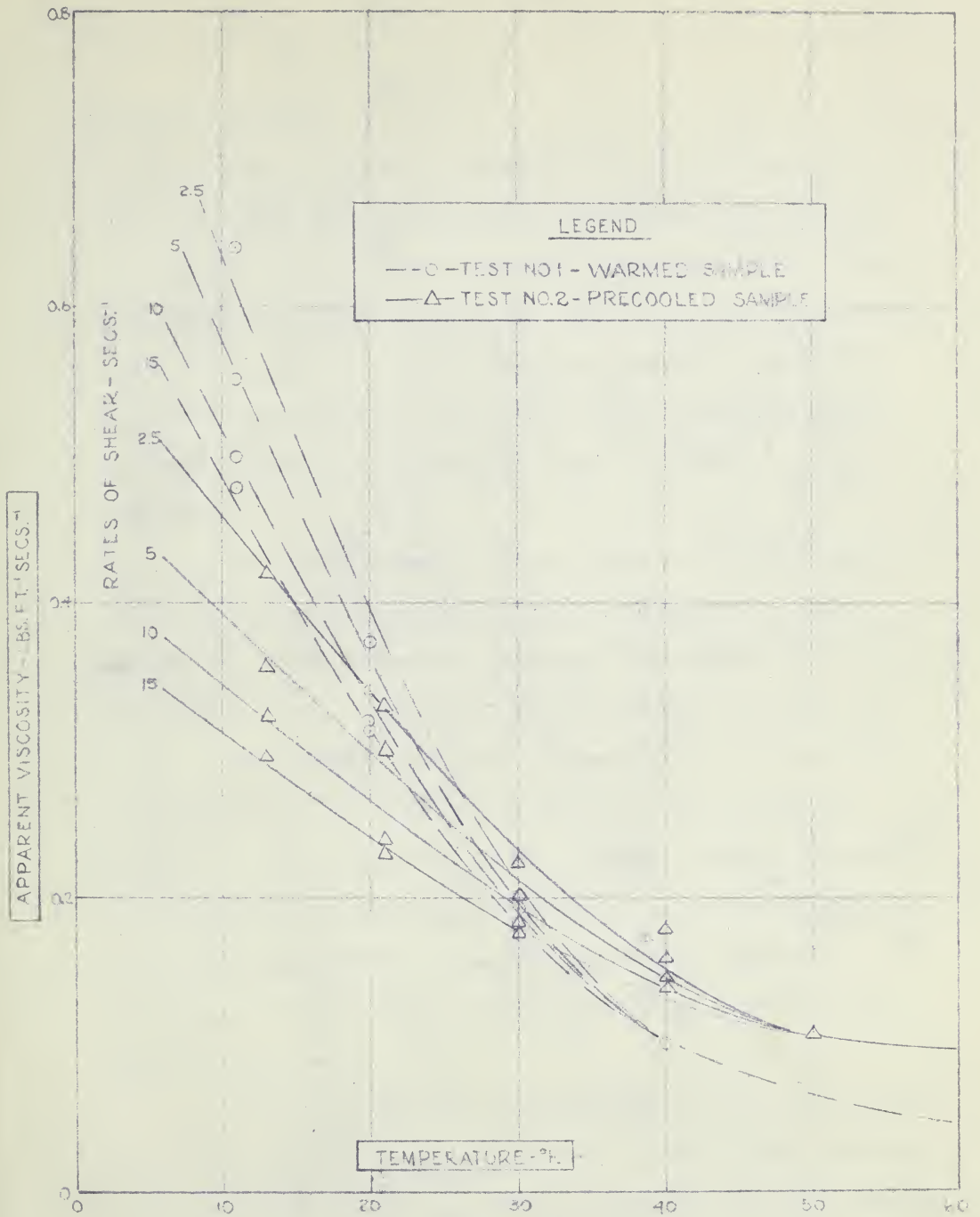


FIGURE 26

APPARENT VISCOSITIES OF EXCELSIOR D2 CRUDE OIL PRECOOLED TO 10°F. AND PREWARMED TO 60°F.

Leduc D2 Crude Oil

Testing a sample of Leduc D2 crude oil, obtained at 60°F. and cooled to the successively lower temperatures indicated in Table 14, yielded the data tabulated in the same table. These data are shown plotted in Figure 27. They all appear reliable and indicate that the transition in behavior occurred in the 27°F. to 40°F. temperature range. Data at more testing temperatures would have been advantageous in that they would have served to narrow this range.

The test of a second sample, precooled to 0°F., resulted in data tabulated in Table XV and plotted in Figure 28. This plot shows that the transition occurred in the 31°F. to 39°F. temperature range. These data are also considered reliable.

The apparent viscosity - temperature data derived from Figures 27 and 28 are tabulated in Table XXII and plotted in Figure 29. This plot shows that the prewarmed crude oil possesses appreciably greater apparent viscosities at all rates of shear at temperatures below 38°F. Above 39°F. the absolute viscosity (Newtonian) of the precooled crude oil is higher than that of the prewarmed crude oil.

The transition points are indicated to be at 33°F. in the case of the precooled crude and 39°F. in the case of the prewarmed crude. No waxing was observed at any temperature during the testing of either sample.

Lebanon ES Crude Oil

Testing a sample of Lebanon ES crude oil, obtained at 60°F. and cooled to the successively lower temperatures indicated in Table II, yielded the data tabulated in the same table. These data are shown plotted in Figure 27. They all appear reliable and indicate that the transition in behavior occurred in the 37°F. to 40°F. temperature range. Data at more testing temperatures would have been advantageous in that they would have served to narrow this range.

The test of a second sample, procured at 60°F., resulted in data tabulated in Table IV and plotted in Figure 28. This plot shows that the transition occurred in the 31°F. to 32°F. temperature range. These data are also considered reliable.

The apparent viscosity - temperature data derived from

Figures 27 and 28 are tabulated in Table XII and plotted in Figure 29. This plot shows that the presumed crude oil possesses appreciably greater apparent viscosities at all rates of shear at temperatures below 36°F. Above 36°F. the absolute viscosity (reciprocal) of the presumed crude oil is higher than that of the presumed crude oil.

The transition points are indicated to be at 33°F. in the case of the presumed crude oil and at 31°F. in the case of the presumed crude. No waxing was observed at any temperature during the testing of either sample.

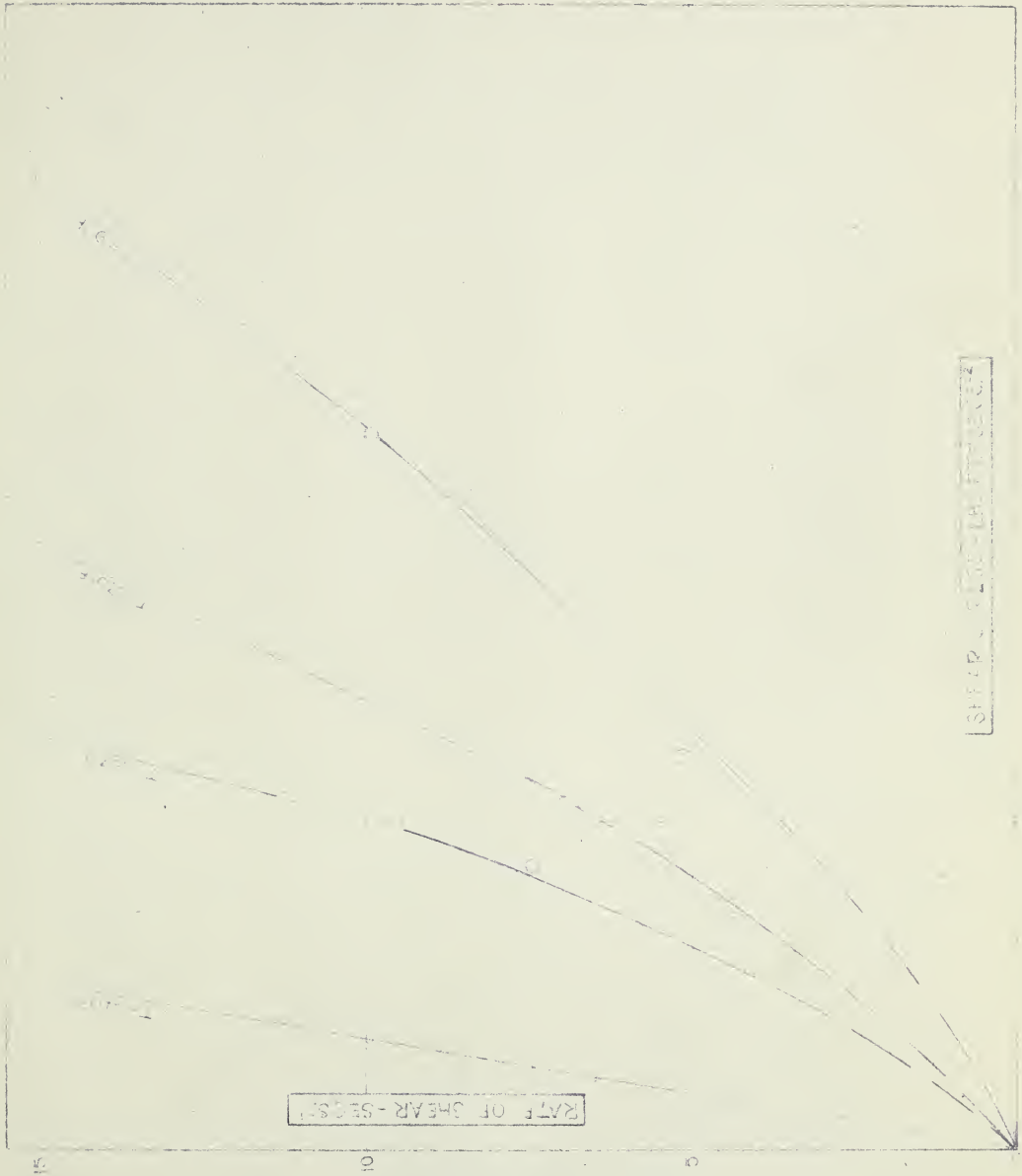


FIGURE 27
TEST NO.1: RHEOLOGICAL PROPERTIES OF LEDUC D2 CRUDE OIL PREWARMED TO 60°F.

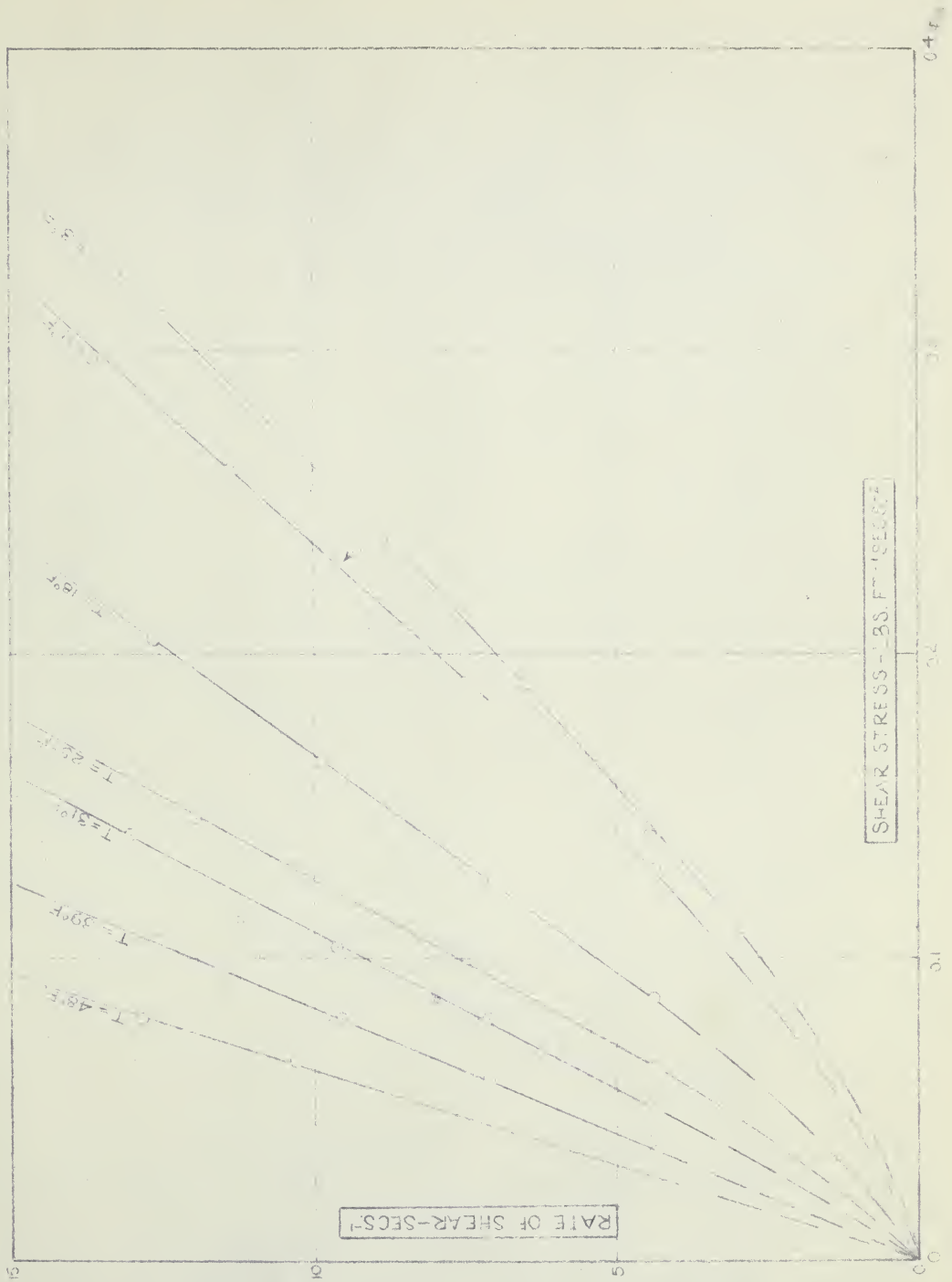


FIGURE 28

TEST NO. 2: RHEOLOGICAL PROPERTIES OF LEDUC D2 CRUDE OIL PRECOOLED TO 0°F.

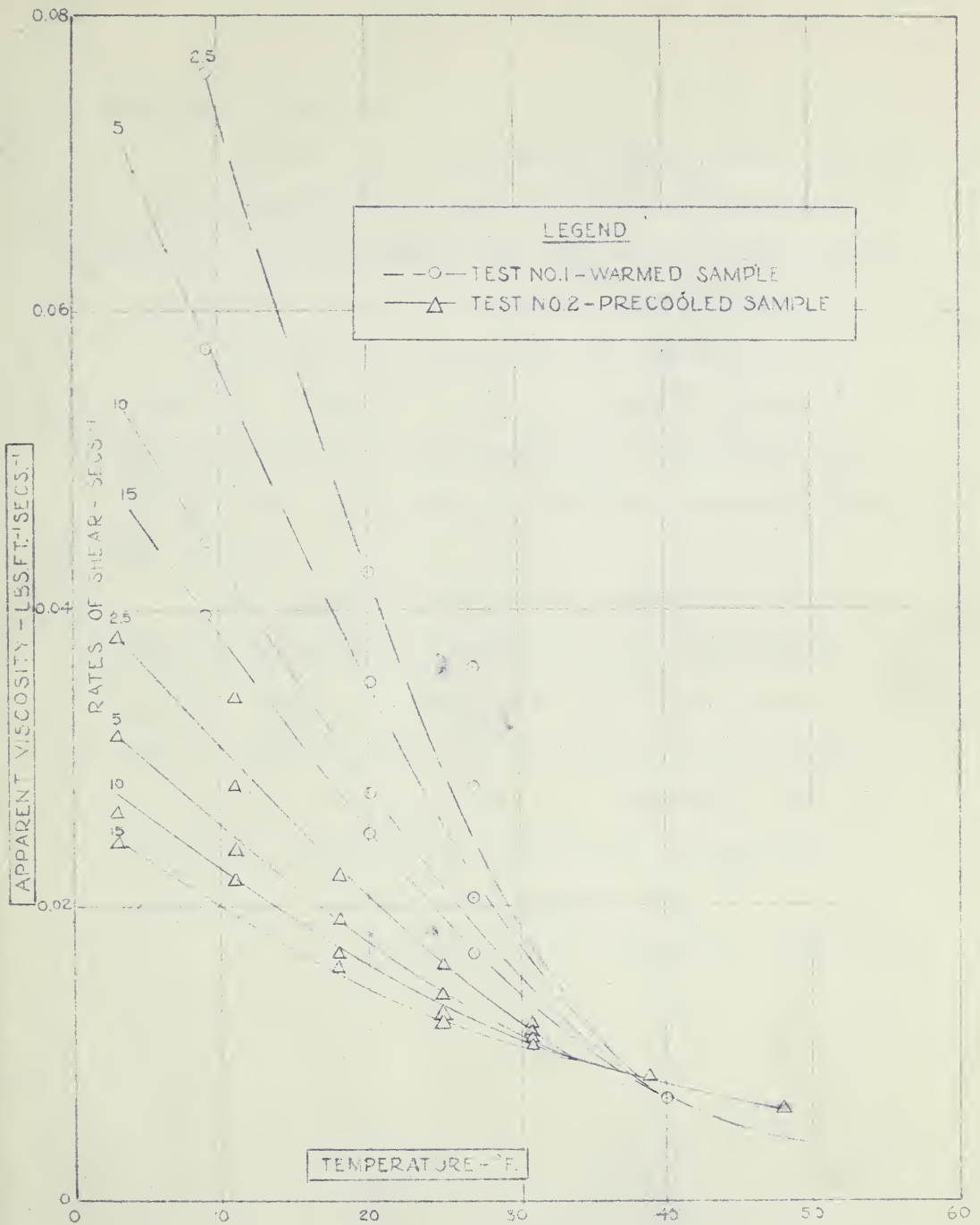


FIGURE 29

APPARENT VISCOSITIES OF LEDUC D2 CRUDE OIL PREWARMED TO 60°F.
AND PRECOOLED TO 0°F.

Golden Spike Crude Oil

Test No. 1 on a Golden Spike crude oil sample, prewarmed to 70 F., resulted in data tabulated in Table XVI and plotted in Figure 30. The plot indicates that the data are reliable and that the transition in behavior occurred between 35°F. and 45°F.

Test No. 2 on the same crude oil, precooled to 0°F., yielded data listed in Table XVII and plotted in Figure 31. These data indicated that the transition in the behavior of the crude oil sample from Newtonian to non-Newtonian occurred between 39°F. and 50°F.

The apparent viscosity - temperature data derived from Figures 30 and 31 are tabulated in Table XXII and plotted in Figure 32. This plot shows that the apparent viscosities of the prewarmed crude oil at 5°F. are three times those of the precooled crude oil at the same temperature. At temperatures above 48°F. the absolute viscosity of the precooled oil (now Newtonian) is slightly higher than that of the prewarmed oil.

No waxing was observed at any temperature during testing of either sample.

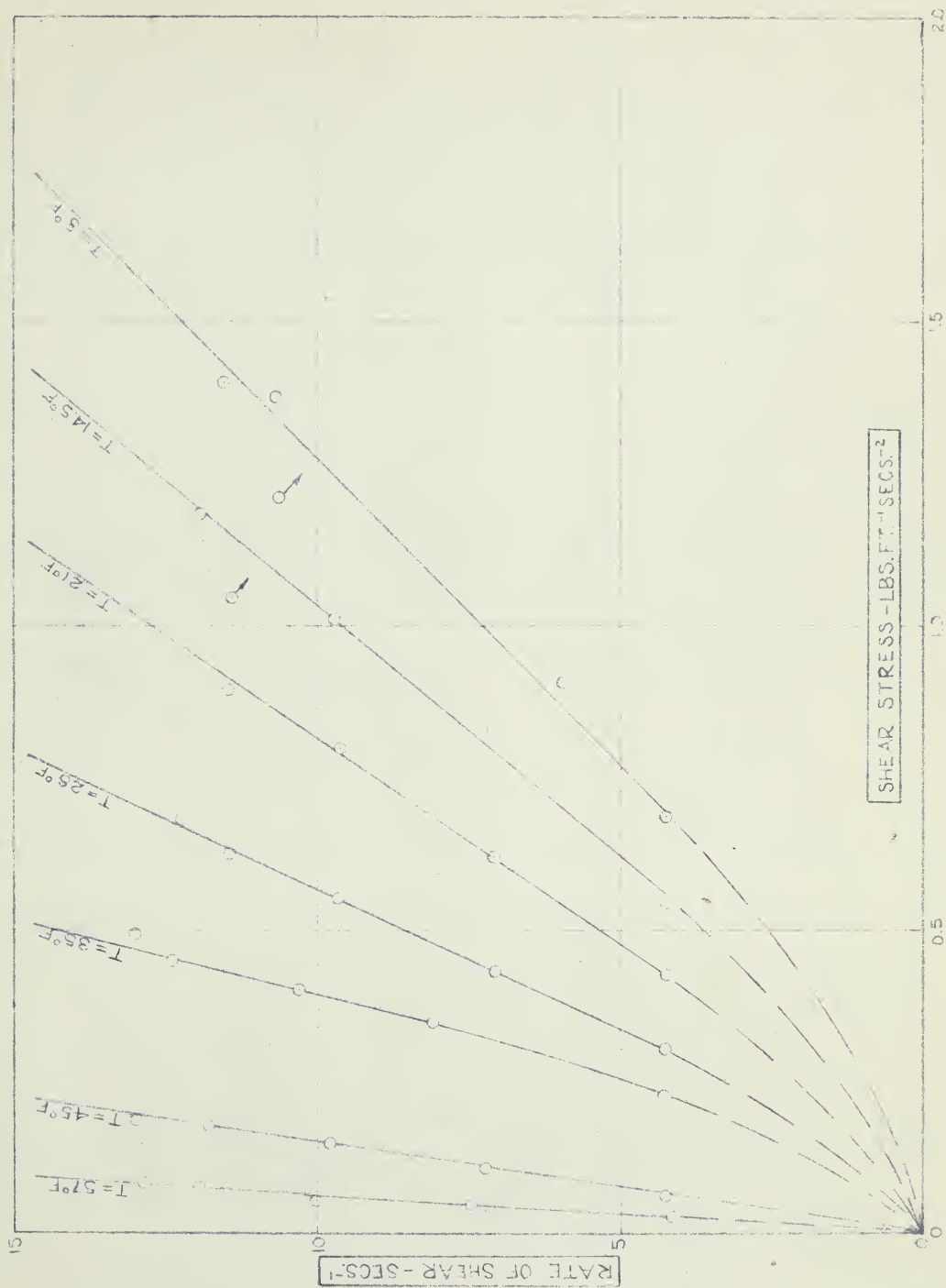


FIGURE 30

TEST NO.1: RHEOLOGICAL PROPERTIES OF GOLDEN SPIKE CRUDE OIL PREWARMED TO 70°F.

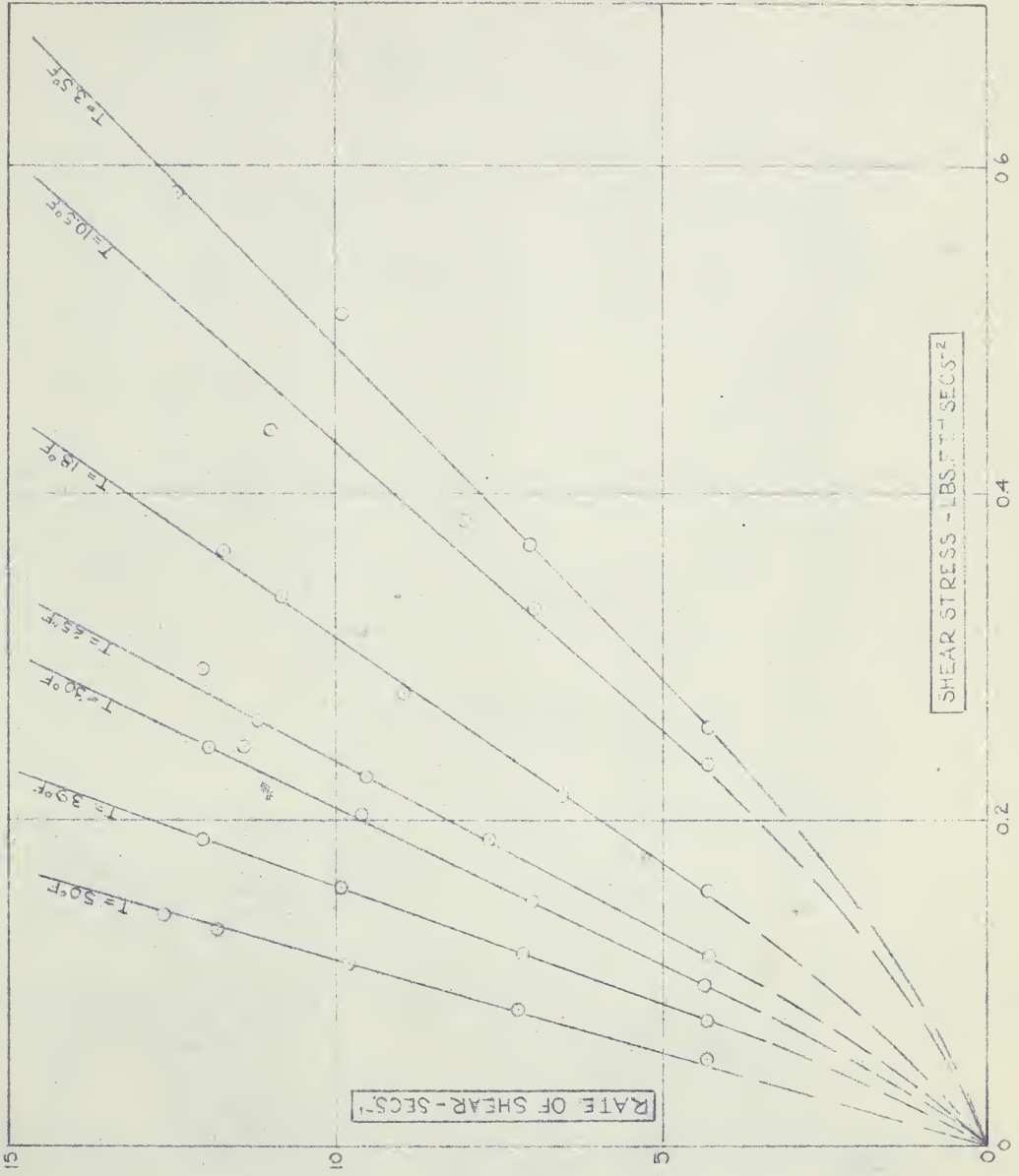


FIGURE 31
TEST NO. 2: RHEOLOGICAL PROPERTIES OF GOLDEN SPIKE CRUDE OIL PRECOOLED TO 0°F.

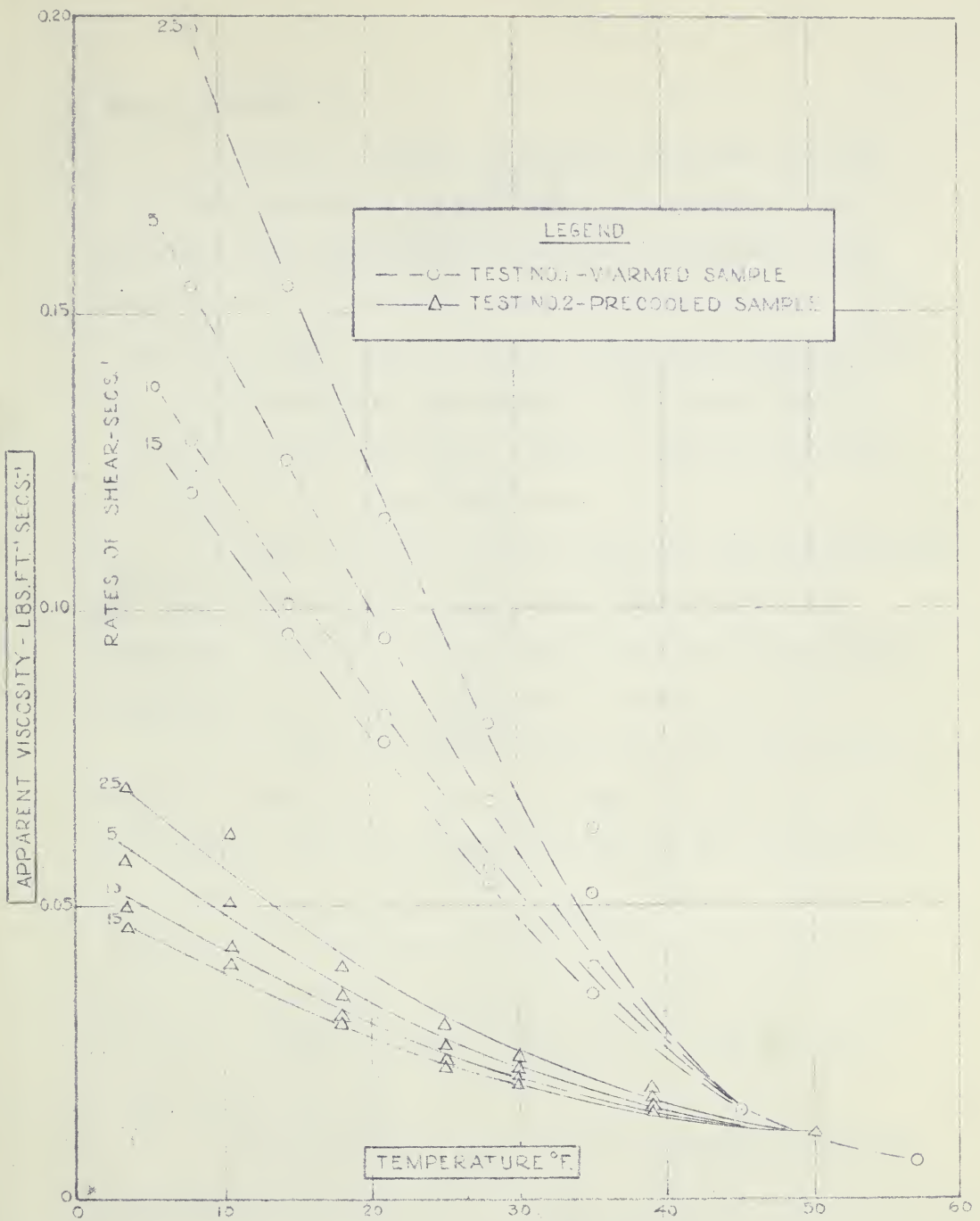


FIGURE 32

APPARENT VISCOSITIES OF GOLDEN SPIKE CRUDE OIL PREWARMED TO 70°F. AND PRECOOLED TO 0°F.

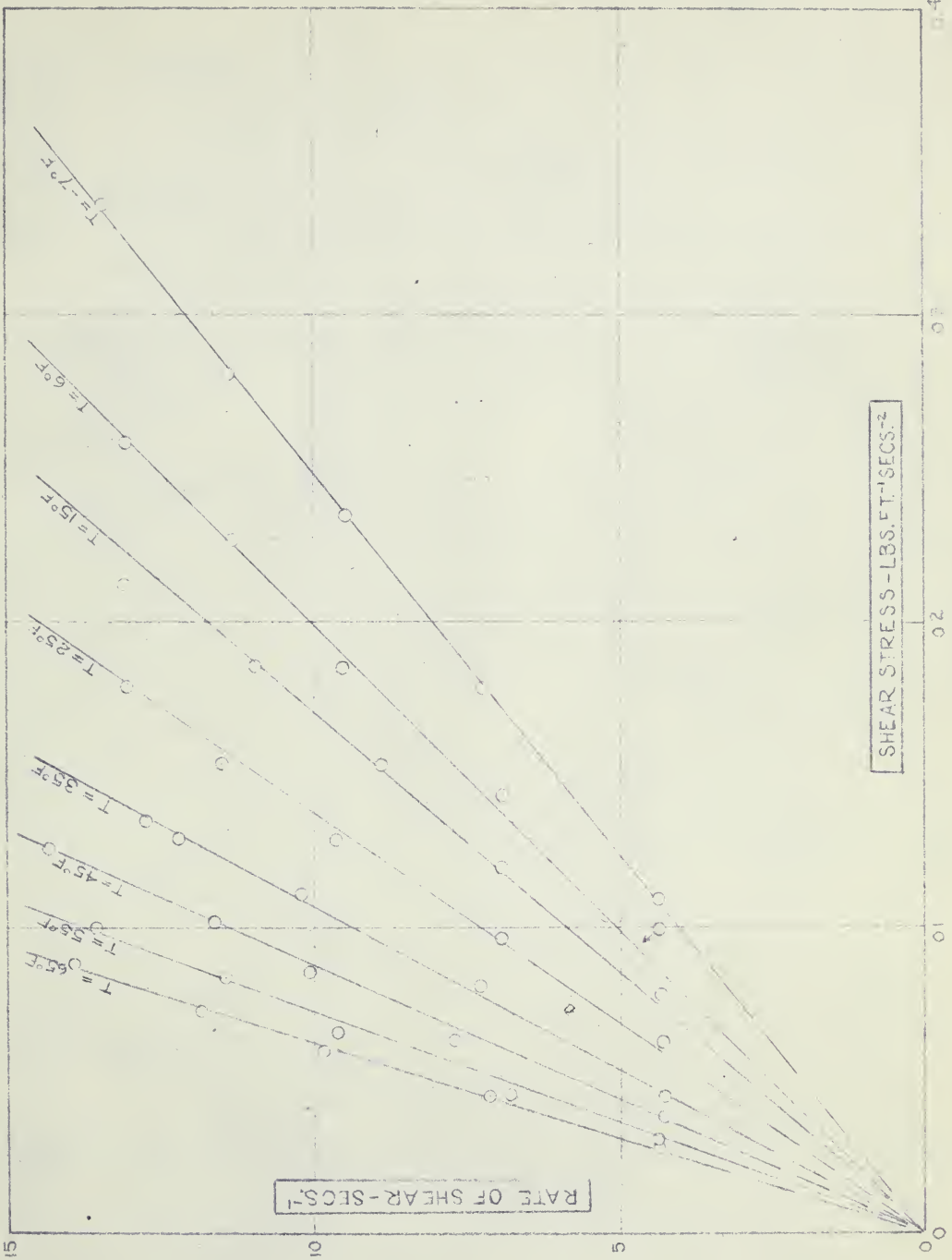
Duhamel D2 Crude Oil

A sample of Duhamel D2 crude oil, prewarmed to 70°F., when tested resulted in the data listed in Table XVIII. When these data were plotted in Figure 33 they revealed that the oil sample behaved as a Newtonian liquid throughout the -7°F. to 65°F. temperature range. All the curves are linear, pass through almost all of the plotted data, and intersect at the origin. This was the only oil tested that showed a behavior similar to Newtonian liquids at all the testing temperatures.

A test of a second sample of the same crude oil, precooled to 0°F., yielded data tabulated in Table XIX and plotted in Figure 34. These data indicate that the crude oil behaved as a Newtonian only after its temperature had reached about 48°F.

The apparent viscosity - temperature data derived from Figures 33 and 34 are listed in Table XXII and plotted in Figure 35. They indicate that the apparent viscosities of the prewarmed crude oil at 0°F. are about twice as large as the absolute viscosity of the precooled oil at the same temperature. The prewarmed crude oil behaves as a Newtonian at temperatures above 29°F. and its absolute viscosity is slightly lower than that of the precooled crude at temperatures above 35°F.

No wax deposition was observed at any temperature during testing of either sample.



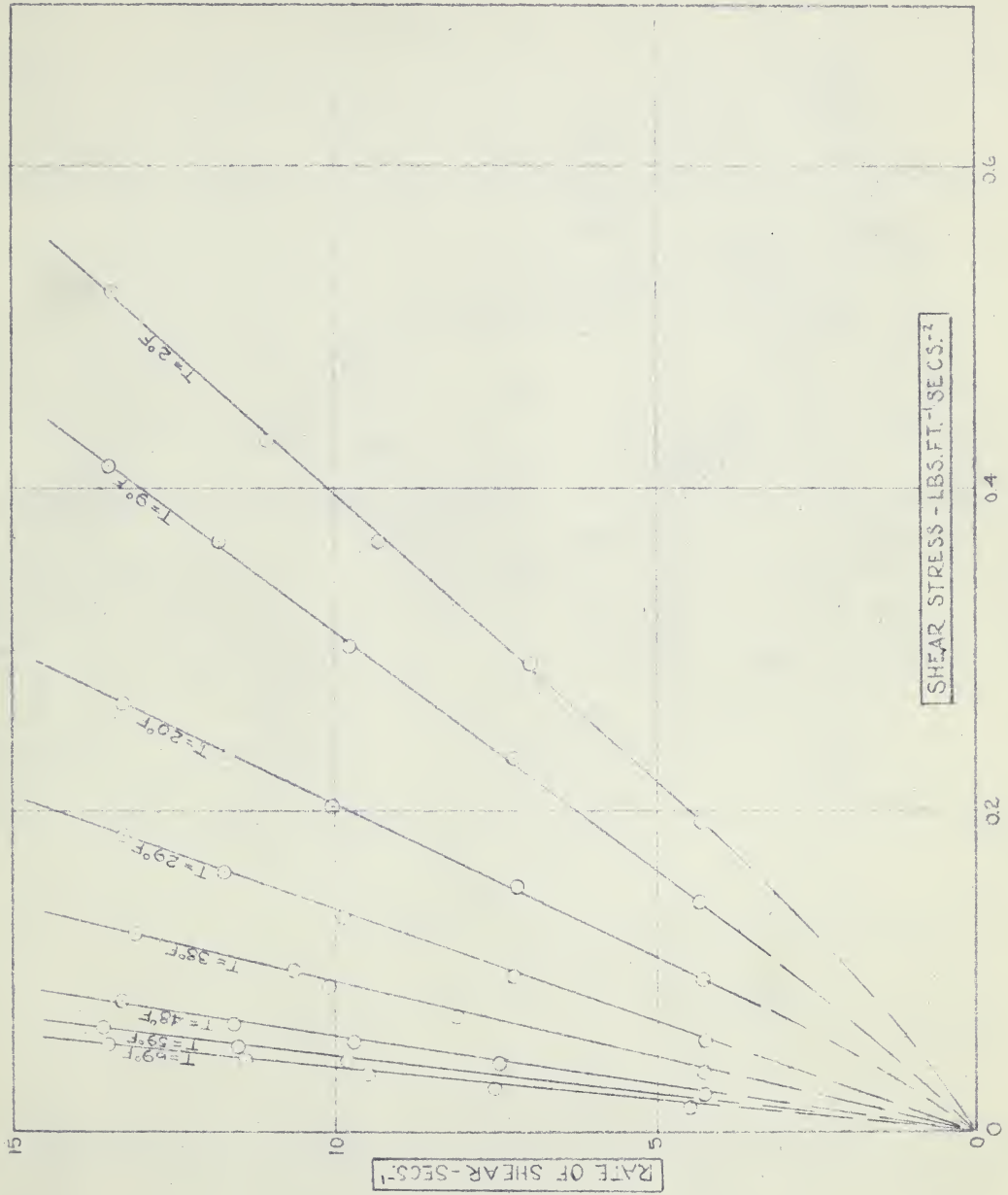


FIGURE 34

TEST NO. 2: RHEOLOGICAL PROPERTIES OF DUHAMEL D2 CRUDE OIL PREHEATED TO 70°F .

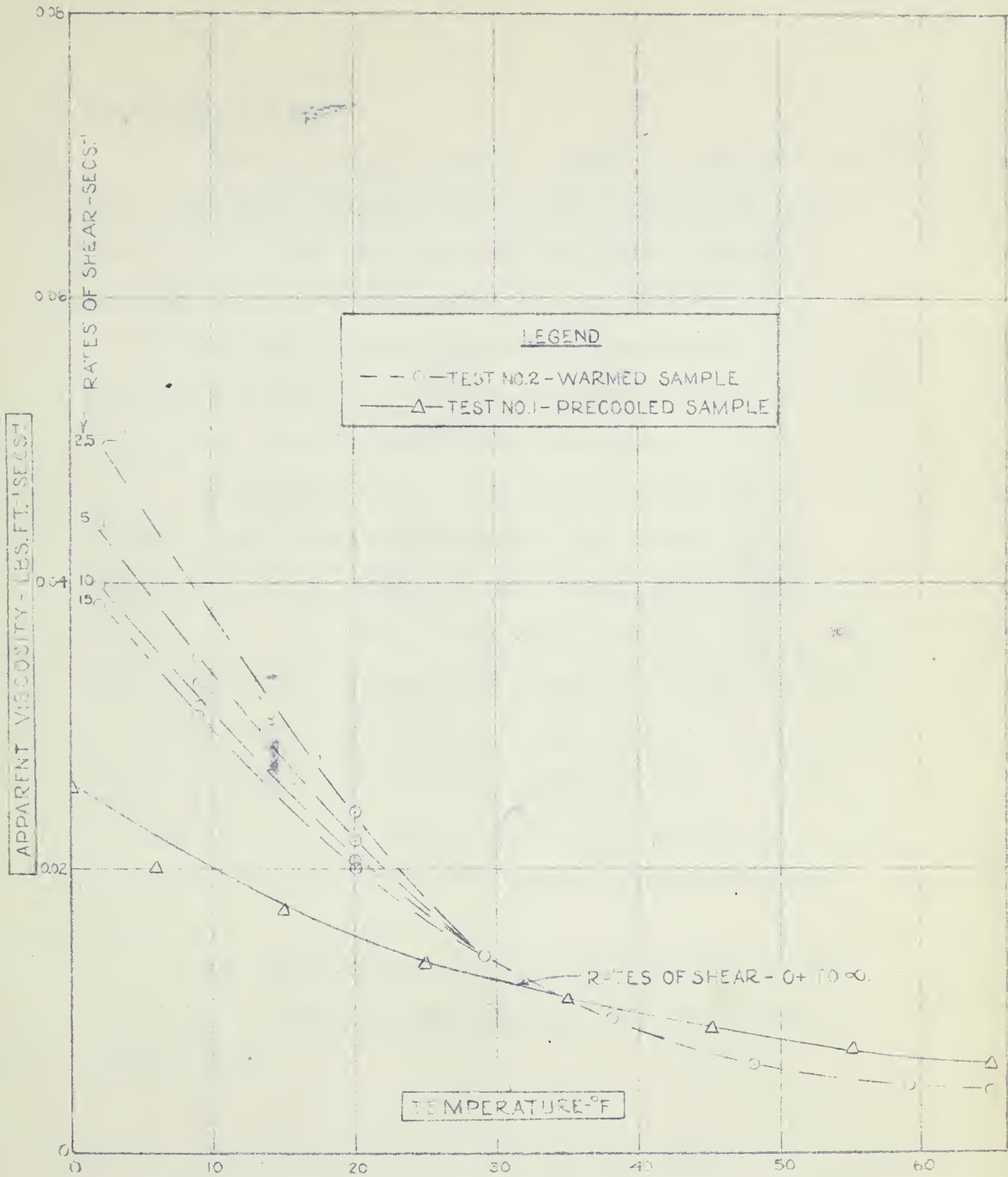


FIGURE 35

APPARENT VISCOSITIES OF DUHAMEL D2 CRUDE OIL PRECOOLED TO -10°F
 AND PREWARMED TO 70°F .

Duhamel D3 Crude Oil

The first sample of Duhamel D3 crude oil, precooled to 0°F., when tested resulted in data listed in Table XX and plotted in Figure 36. They show that the transition from non-Newtonian to Newtonian behavior occurred between 50°F. and 60°F.

The test of second sample, previously warmed to 70°F., yielded data tabulated in Table XXI and plotted in Figure 37. These data show the transition occurred between 45°F. and 55°F.

From Figures 36 and 37 the apparent viscosities at different rates of shear and temperatures were derived and are listed in Table XXII. These data were then plotted in Figure 38. This plot shows that prewarmed Duhamel D3 crude oil at 5°F. has about twice as large apparent viscosities as prewarmed Duhamel D3 crude at the same temperature. Furthermore, its apparent viscosities are higher throughout the 5°F. to 60°F. temperature range. The plot also indicates the transition in behavior to be at 45°F. in the case of the prewarmed crude and at 59°F. in the case of the precooled crude.

Wax deposition was observed at temperatures below 30°F. when testing the precooled crude and below 20°F. when testing the prewarmed crude.

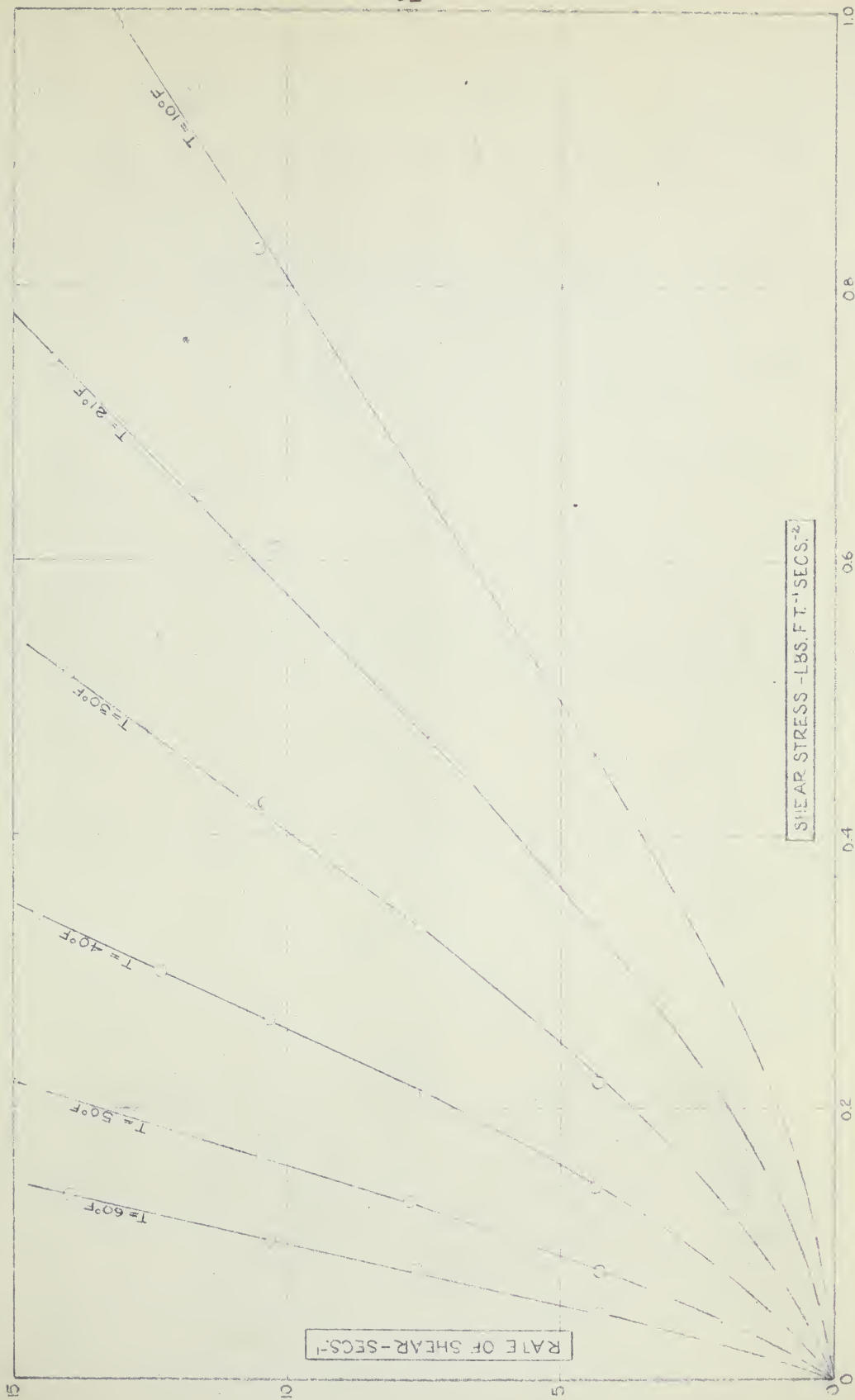


FIGURE 36

TEST NO. 1: RHEOLOGICAL PROPERTIES OF DUHAMEL D3 CRUDE OIL PRECOOLED TO 70°F .

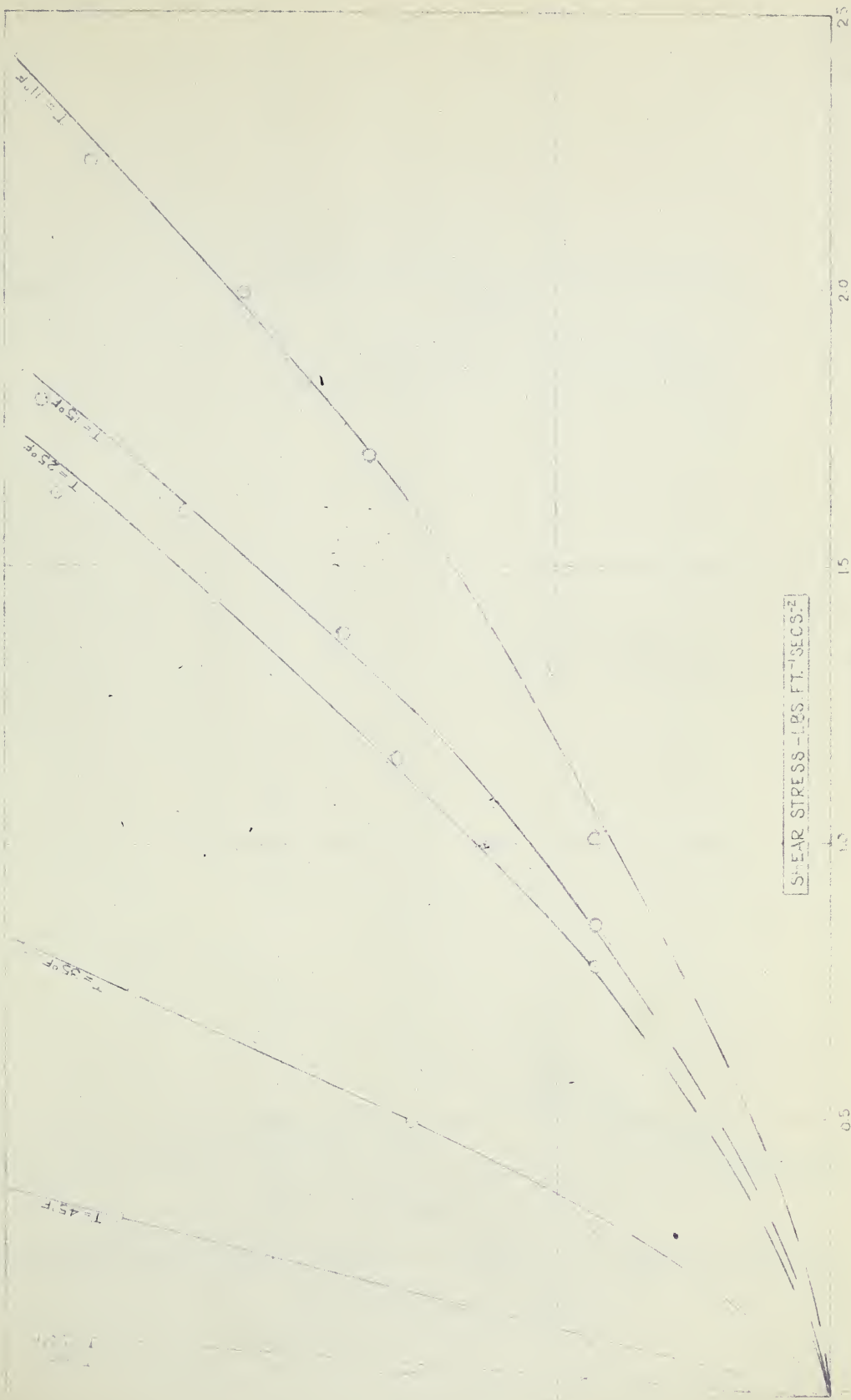


FIGURE 37

TEST NO. 2: RHEOLOGICAL PROPERTIES OF DUHAMEL D3 CRUDE OIL PRECOOLED TO 0°F.

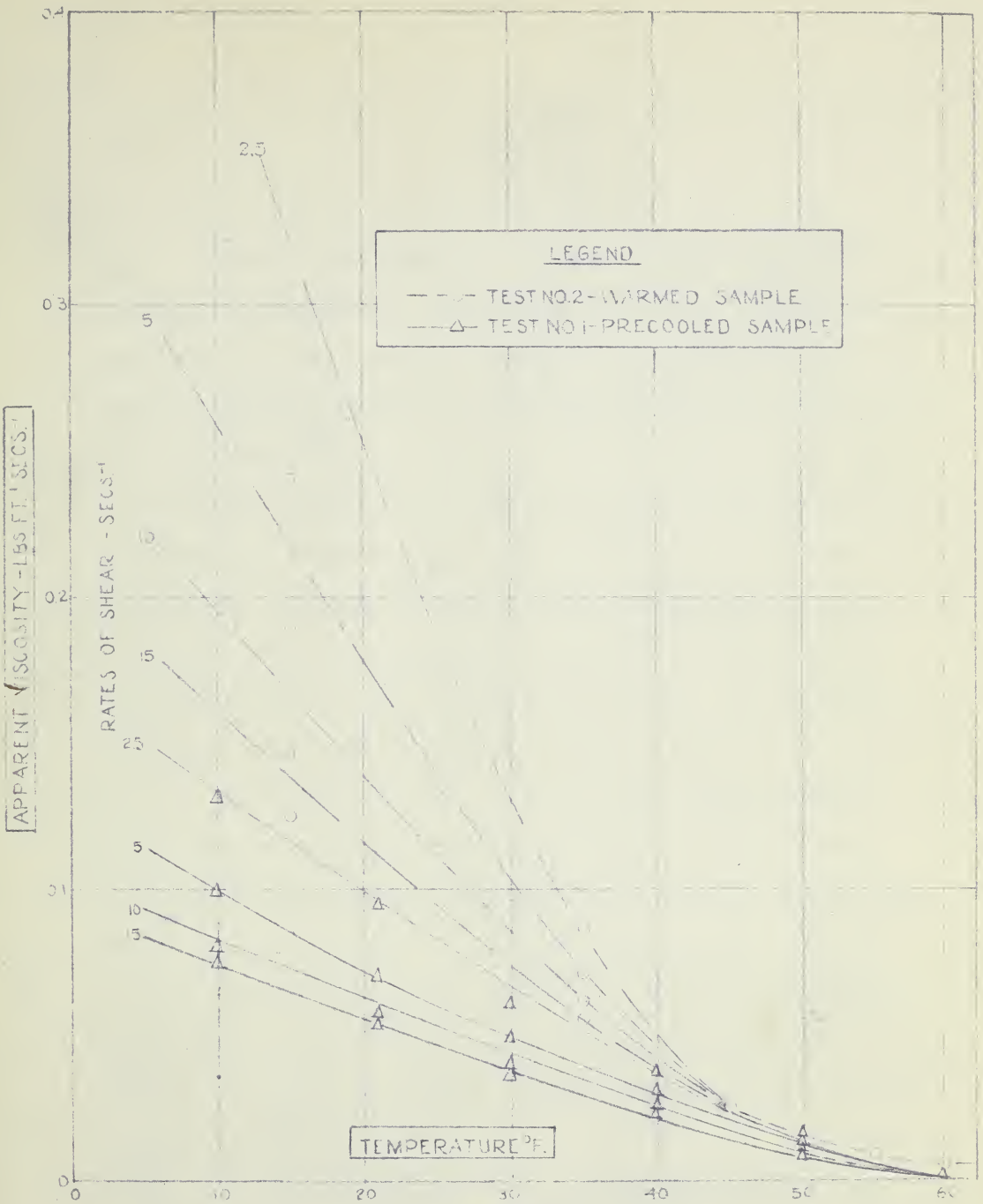


FIGURE 38

APPARENT VISCOSITIES OF DUHAMEL D3 CRUDE OIL PRECOOLED TO 0°F.
and PREWARMED TO 70°F.

CONCLUSIONS

There are two important conclusions to be drawn from the results of this research. The first is that the selected Alberta crude oils, with the exception of precooled Duhamel D2, do not behave as Newtonian liquids at temperatures below approximately 40°F. Below this temperature the apparent viscosity varies with the rate of shear. Furthermore, the results of the tests strengthen the assumption that the oils behave as pseudoplastics at the lower temperatures. The rate of shear - shearing stress curve of any one oil at a constant temperature commences at the origin and approaches a straight line at high shear stresses. The apparent viscosity decreases with increasing shearing stress.

The second conclusion is that thermal treatment has a decided effect on the rheological properties of a specific crude oil. The apparent viscosities of crude oils prewarmed to 70°F. were always found to be larger than those of identical crude oils which had been cooled to 0°F. before testing. One of the shortcomings of this research, which prevents more specific conclusions, is that the thermal histories of the samples, prior to testing in the laboratory, were not established definitely.

It was also observed that at higher temperatures, after an oil had ceased to behave as a non-Newtonian, the absolute viscosity

of the precooled sample was often slightly larger than that of a prewarmed sample at the same temperature. This is contrary to the belief that, once an oil exceeds the temperature below which it behaves as a non-Newtonian, its absolute viscosity is constant regardless of previous thermal treatment. It is not thought wise, however, to draw any general conclusion in this respect without data obtained from testing oils with more than two previous thermal histories.

With these results it is possible to solve a crude oil flow problem by means of the conventional (Newtonian) fluid flow equations. These equations are:

$$\Delta P = \frac{f L \rho V^2}{2 D} \quad (16)$$

$$\text{and } f = \phi \left(\frac{DV\rho}{\mu} \right) \quad (17)$$

where ΔP = pressure drop, lbs./ft.sec.² or poundals/ft.²

L = length of pipe, ft.,

ρ = density of the oil, lbs./ft.³,

V = mean velocity of flow, ft./sec.,

D = diameter of pipe, ft.,

μ = viscosity (apparent or absolute) lbs./ft.sec.

and f = friction factor, dimensionless.

The only difficulty in the manipulation of this equation is that the velocity of flow must be known so that the rate of shear may be calculated before the friction factor can be determined. The solution necessarily follows a trial and error procedure.

In some cases the apparent viscosities may be required at rates of shear much higher than 15 sec.⁻¹. These may be obtained

from the reciprocal slope of the straight line portion of the curve corresponding to the required temperature.

If the data obtained had indicated that the crude oils behave as Bingham plastics the flow problems could be solved with ~~with~~ the use of the Buckingham equation (7). This behavior was not indicated in this research. Neither was Bingham body behavior discounted entirely because of the inability to obtain shearing stresses at zero to 4 sec.⁻¹ rates of shear.

The results of this research are not entirely satisfactory because vaporization of the crude oils during testing undoubtedly caused a change in the rheological properties. Furthermore, the rheological properties were determined at atmospheric pressure, not at pressures up to 1000 p.s.i. commonly encountered in crude oil pipelines. Anderson (2) has shown that increased pressure has the effect of increasing the apparent viscosities of crude oils substantially at low temperatures.

To overcome these two disadvantages serious thought was given to the possibility of designing an instrument that would measure the rheological properties in the absence of vaporization and under pressures greater than atmospheric. A thorough literature review revealed that a suitable pilot pipeline unit would be capable of measuring the properties at rates of shear, pressures, and temperatures similar to those commonly encountered in large diameter pipeline operations. Such a unit was designed and its essential features are discussed below.

from the horizontal slope of the straight line portion of the curve corresponding to the required temperature.

If the data obtained had indicated that the curve was

below a certain point the flow problem could be solved with

the use of the Manning equation (7). This behavior was

not indicated in this research. Neither was Manning's behavior

discussed entirely because of the inability to obtain accurate

viscosity at rates of 4 sec.-1 rates of shear.

The results of this research are not entirely satisfactory

because of the variation of the curve data during testing

and possibly caused a change in the rheological properties. Further

more, the rheological properties were determined at atmospheric

pressure, not at pressures up to 1000 p.s.i. commonly encountered in

large oil pipelines. Anderson (2) has shown that increased pressure

has the effect of increasing the apparent viscosities of crude oils

substantially at low temperatures.

To overcome these two disadvantages further thought was

given to the possibility of designing an instrument that would

measure the rheological properties in the absence of vaporization

and under pressures greater than atmospheric. A laboratory instrument

review revealed that a suitable pilot pipeline unit would be capable

of measuring the properties at rates of shear, pressure, and

temperatures similar to those commonly encountered in large diameter

pipeline operations. Such a unit was designed and the essential features

are discussed below.

Three 30 foot test sections of $3/8$ inch, $\frac{1}{2}$ inch, and $5/8$ inch O.D. seamless, stainless steel tubing are passed through an 8 inch cylindrical shell. The oil to be tested would be circulated through one of these test sections at a maximum rate of 20 Imperial gallons per minute by means of a gear pump. A volumetric vessel would measure the rate of flow and pressure gauges at either end of the test sections would indicate the corresponding pressure drop. Temperature control at any temperature between 0°F. and 70°F. would be maintained by a 3 H.P. compressor propane refrigerator connected to the cylindrical constant temperature shell. The only unknown factor would then be the apparent viscosity which could be evaluated by means of conventional fluid flow equations.

This unit, when constructed, will be capable of measuring apparent viscosities of most Alberta crude oils in the range of Reynolds numbers from zero to 30,000 and at pressures up to 1000 psi. This Reynolds number range is below the maximum of 60,000 encountered in some large diameter lines. However, attaining a Reynolds number of 60,000 in a pilot unit would require excessive power and measuring facilities.

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APPENDIX A

END EFFECT CORRECTION AND TORSION

WIRE CALIBRATION DATA

TABLE I

Calibration of 34 Gauge Torsion Wire
and determination of end effect correction
using a 149.8 centipoise @ 70°F. Standard Oil

Depth of Immersion cm.	Number of Revolutions	Time secs.	Rotational Speed r.p.m.	Deflection Degrees
0.6	15	59.2	15.2	28.7
	20	63.0	19.0	34.0
	25	61.4	24.4	46.3
	30	61.5	29.3	56.0
	35	62.9	33.4	63.7
	40	58.2	41.2	84.0
1.6	15	60	15.0	59.3
	20	63.3	19.0	74.5
	25	61.5	24.4	93.0
	30	61.5	29.3	111.5
	35	62.9	33.4	124.5
	40	58.3	41.2	153.7
2.6	15	60	15.0	86.3
	20	62.3	19.25	111.7
	25	60.5	24.8	148.5
	30	61.0	29.5	177.5
	35	62.5	33.6	200.0
	40	59.0	40.7	239.5
3.6	15	59.0	15.2	123.0
	20	63.0	19.0	158.0
	25	61.7	24.3	197.3
	30	61.1	29.5	235.7
	35	61.4	33.6	269.0

TABLE II A

Calibration of 34 Gauge Torsion Wire
and determination of end effect correction
using a 149.8 centipoise @ 70°F. standard oil

Depth of Immersion cm.	Number of Revolutions	Time secs.	Rotational Speed r.p.m.	Deflection Degrees
0.6	20	59.8	20.1	33.5
	25	60.5	24.8	42.3
	20	59.7	30.2	49.3
	35	59.7	35.2	57.0
	40	59.7	40.2	65.3
1.6	20	59.8	20.1	72.0
	25	60.1	25.0	89.3
	30	59.7	30.2	107.5
	35	60.1	35.0	122.4
	40	59.7	40.2	139.3
2.6	20	59.8	20.1	111.7
	25	61.0	24.6	133.7
	30	59.8	30.1	163.7
	35.	60.0	35.0	192.8
	40	60.1	40.0	220.0
3.6	20	60.0	20.0	149.0
	25	60.6	24.8	182.0
	30	60.0	30.0	218.3
	35	59.7	35.2	261.0
	40	60.0	40.0	293

TABLE II B

Determination of the 34 Gauge Torsion Wire Calibration
Constant K.

Corrected Depth of Immersion - h cms.	Constant S = $1055/h$ ft. ⁻³	$/\theta$ from Fig. 11 R.P.M.deg. ⁻¹	Constant K = 0.01054 lbs.ft. ² sec. ⁻² deg. ⁻¹	Comparative Weight	Constant K multiplied by compara- tive weight
0.85	1240	0.613	5.21×10^{-6}	1	5.21×10^{-6}
1.85	570	0.286	5.30×10^{-6}	2	10.60×10^{-6}
2.85	371	0.182	5.175×10^{-6}	3	15.53×10^{-6}
3.85	275	0.136	5.22×10^{-6}	4	20.88×10^{-6}
				Total = 10	52.22×10^{-6}

$$\text{Average Constant K} = \frac{52.22 \times 10^{-6}}{10}$$

$$= 5.222 \times 10^{-6} \text{ lbs. ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1}$$

TABLE III A

Calibration of 32 Gauge Torsion Wire
and determination of end effect correction
using a 310.3 centipoise at 70°F. standard oil

Depth of Immersion cm.	Number of Revolutions	Time secs.	Rotational Speed r.p.m.	Deflection Degrees
0.6	15	61.4	14.65	19.5
	20	60.5	19.85	26.5
	25	60.0	25	33.5
	30	61.1	29.5	39.0
	35	60.3	34.8	46.3
	40	60.9	39.4	53.0
1.6	15	51.1	14.7	41.8
	20	60.8	19.75	56.3
	25	60.0	25.0	70.7
	30	61.2	29.4	82.0
	35	60.1	35.0	99.0
	40	60.9	39.4	110.7
2.6	15	61.1	14.7	62.7
	20	60.7	19.8	82.5
	25	60.0	25	106.5
	30	61.5	29.3	129.0
	35	60.6	34.7	152.5
	40	60.9	39.4	172.0
3.6	15	61.6	14.65	86.3
	20	60.3	19.9	117.8
	25	59.9	25.0	145.7
	30	61.4	29.4	169.5
	35	60.3	34.8	207.3
	40	60.9	39.4	235.0

TABLE III B

Determination of 32 Gauge Torsion Wire Calibration Constant K

Corrected Depth of Immersion - h cms.	Constant S = $1055/h$ ft. ⁻³	$/\theta$ from Figure 12. RPM. deg. ⁻¹	Constant K = 0.0218 lbs.ft. ² sec. ⁻² deg. ⁻¹	Comparative Weight	Constant K Multiplied by Comparative Weight
0.85	1240	0.743	1.306×10^{-5}	1	1.306×10^{-5}
1.85	570	0.355	1.356×10^{-5}	2	2.712×10^{-5}
2.85	371	0.229	1.347×10^{-5}	3	4.041×10^{-5}
3.85	275	0.168	1.332×10^{-5}	4	5.328×10^{-5}
Total = 10					13.387×10^{-5}

$$\text{Average Constant K} = \frac{13.387 \times 10^{-5}}{10}$$

$$= 1.339 \times 10^{-5} \text{ lbs. ft.}^2 \text{ sec.}^{-2} \text{ deg.}^{-1}$$

EXERCISE 1

Consider the following data set (the data are from a real experiment).

Experiment	Condition	Response	Response	Response	Response
1	1	1.0	1.0	1.0	1.0
2	1	1.0	1.0	1.0	1.0
3	1	1.0	1.0	1.0	1.0
4	1	1.0	1.0	1.0	1.0
5	1	1.0	1.0	1.0	1.0
6	1	1.0	1.0	1.0	1.0
7	1	1.0	1.0	1.0	1.0
8	1	1.0	1.0	1.0	1.0
9	1	1.0	1.0	1.0	1.0
10	1	1.0	1.0	1.0	1.0
11	1	1.0	1.0	1.0	1.0
12	1	1.0	1.0	1.0	1.0
13	1	1.0	1.0	1.0	1.0
14	1	1.0	1.0	1.0	1.0
15	1	1.0	1.0	1.0	1.0
16	1	1.0	1.0	1.0	1.0
17	1	1.0	1.0	1.0	1.0
18	1	1.0	1.0	1.0	1.0
19	1	1.0	1.0	1.0	1.0
20	1	1.0	1.0	1.0	1.0
21	1	1.0	1.0	1.0	1.0
22	1	1.0	1.0	1.0	1.0
23	1	1.0	1.0	1.0	1.0
24	1	1.0	1.0	1.0	1.0
25	1	1.0	1.0	1.0	1.0
26	1	1.0	1.0	1.0	1.0
27	1	1.0	1.0	1.0	1.0
28	1	1.0	1.0	1.0	1.0
29	1	1.0	1.0	1.0	1.0
30	1	1.0	1.0	1.0	1.0
31	1	1.0	1.0	1.0	1.0
32	1	1.0	1.0	1.0	1.0
33	1	1.0	1.0	1.0	1.0
34	1	1.0	1.0	1.0	1.0
35	1	1.0	1.0	1.0	1.0
36	1	1.0	1.0	1.0	1.0
37	1	1.0	1.0	1.0	1.0
38	1	1.0	1.0	1.0	1.0
39	1	1.0	1.0	1.0	1.0
40	1	1.0	1.0	1.0	1.0
41	1	1.0	1.0	1.0	1.0
42	1	1.0	1.0	1.0	1.0
43	1	1.0	1.0	1.0	1.0
44	1	1.0	1.0	1.0	1.0
45	1	1.0	1.0	1.0	1.0
46	1	1.0	1.0	1.0	1.0
47	1	1.0	1.0	1.0	1.0
48	1	1.0	1.0	1.0	1.0
49	1	1.0	1.0	1.0	1.0
50	1	1.0	1.0	1.0	1.0
51	1	1.0	1.0	1.0	1.0
52	1	1.0	1.0	1.0	1.0
53	1	1.0	1.0	1.0	1.0
54	1	1.0	1.0	1.0	1.0
55	1	1.0	1.0	1.0	1.0
56	1	1.0	1.0	1.0	1.0
57	1	1.0	1.0	1.0	1.0
58	1	1.0	1.0	1.0	1.0
59	1	1.0	1.0	1.0	1.0
60	1	1.0	1.0	1.0	1.0
61	1	1.0	1.0	1.0	1.0
62	1	1.0	1.0	1.0	1.0
63	1	1.0	1.0	1.0	1.0
64	1	1.0	1.0	1.0	1.0
65	1	1.0	1.0	1.0	1.0
66	1	1.0	1.0	1.0	1.0
67	1	1.0	1.0	1.0	1.0
68	1	1.0	1.0	1.0	1.0
69	1	1.0	1.0	1.0	1.0
70	1	1.0	1.0	1.0	1.0
71	1	1.0	1.0	1.0	1.0
72	1	1.0	1.0	1.0	1.0
73	1	1.0	1.0	1.0	1.0
74	1	1.0	1.0	1.0	1.0
75	1	1.0	1.0	1.0	1.0
76	1	1.0	1.0	1.0	1.0
77	1	1.0	1.0	1.0	1.0
78	1	1.0	1.0	1.0	1.0
79	1	1.0	1.0	1.0	1.0
80	1	1.0	1.0	1.0	1.0
81	1	1.0	1.0	1.0	1.0
82	1	1.0	1.0	1.0	1.0
83	1	1.0	1.0	1.0	1.0
84	1	1.0	1.0	1.0	1.0
85	1	1.0	1.0	1.0	1.0
86	1	1.0	1.0	1.0	1.0
87	1	1.0	1.0	1.0	1.0
88	1	1.0	1.0	1.0	1.0
89	1	1.0	1.0	1.0	1.0
90	1	1.0	1.0	1.0	1.0
91	1	1.0	1.0	1.0	1.0
92	1	1.0	1.0	1.0	1.0
93	1	1.0	1.0	1.0	1.0
94	1	1.0	1.0	1.0	1.0
95	1	1.0	1.0	1.0	1.0
96	1	1.0	1.0	1.0	1.0
97	1	1.0	1.0	1.0	1.0
98	1	1.0	1.0	1.0	1.0
99	1	1.0	1.0	1.0	1.0
100	1	1.0	1.0	1.0	1.0

For each condition, the response is 1.0.

For each condition, the response is 1.0.

For each condition, the response is 1.0.

APPENDIX B

SHEARING STRESS - RATE OF SHEAR DATA OBTAINED
FROM TESTS OF THE SELECTED ALBERTA CRUDE OILS

TABLE IV

Rheological Properties of Redwater Crude Oil, Test No. 1

Thermal history: Sample obtained at approximately 50°F, precooled to 10°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
15	14.3	76.0	0.339	4.75
	22.5	109.5	0.488	7.47
	32.2	150.5	0.672	10.7
20	13.35	62.0	0.277	4.50
	24.20	101.5	0.453	8.03
	31.8	128.0	0.571	10.56
	34.0	138.0	0.616	11.30
25	13.7	54.0	0.241	4.55
	20.7	76.0	0.339	6.87
	26.1	92.0	0.410	8.67
	34.5	119.0	0.530	11.45
30	13.7	41.5	0.185	4.55
	21.8	62.0	0.277	7.24
	31.0	85.0	0.379	10.32
	37.9	103.0	0.460	12.59
35	13.8	31.5	0.141	4.62
	25.0	53.5	0.239	8.30
	31.5	65.5	0.292	10.8
	37.0	75.5	0.337	12.3
40	13.75	19.0	0.085	4.57
	20.8	29.0	0.129	6.90
	24.6	35.0	0.156	8.17
	36.5	52.5	0.234	12.12
50	13.8	18.0	0.080	4.58
	20.8	26.0	0.116	6.90
	31.9	39.0	0.174	10.60
	36.0	45.0	0.201	11.95
	40.7	51.0	0.227	13.50

Wax deposition on inside of cup was noted at temperatures below 35°F.

TABLE V

Rheological Properties of Redwater Crude Oil, Test No. 2

Thermal History: Sample obtained at approximately 50°F, warmed to 70°F, cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
70	13.7	6.0	0.027	4.55
	20.4	8.5	0.038	6.77
	24.8	10.7	0.048	8.23
	28.9	12.0	0.054	9.60
	34.7	13.5	0.060	11.53
	35.8	15.0	0.067	11.88
	37.3	16.0	0.071	12.38
60	17.5	12.5	0.056	5.81
	20.3	14.5	0.065	6.74
	23.2	16.5	0.074	7.70
	28.1	19.0	0.085	9.33
	31.7	22.3	0.099	10.53
	46.5	33.5	0.149	15.43
50	21.2	29.5	0.132	7.04
	25.2	33.5	0.150	8.37
	29.5	40.0	0.178	9.80
	33.6	45.5	0.203	11.16
	37.5	47.2	0.210	12.45
	43.8	52.5	0.234	14.55
40	13.75	56.0	0.250	4.57
	19.5	74.5	0.332	6.47
	24.6	90.0	0.402	8.17
	28.8	111.5	0.498	9.56
	34.5	120.5	0.537	11.45
	42.7	146.0	0.651	14.16
37	13.7	80.7	0.360	4.55
	21.2	110.5	0.493	7.04
	26.6	129.0	0.575	8.83
	31.6	144.3	0.644	10.50
	37.4	157.0	0.700	12.42
35	13.7	100.5	0.448	4.55
	21.4	148.0	0.660	7.11
	26.9	173.3	0.773	8.93
	32.8	198.0	0.884	10.90
	38.5	219.5	0.980	12.78
	44.7	246.0	1.097	14.85

Wax deposition was noted at temperatures below 30°F.

TABLE V (continued)

Rheological Properties of Redwater Crude Oil, Test No. 2

Temperature of	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
33	13.7	114.0	0.508	4.55
	17.6	137.5	0.613	5.84
	23.2	175.7	0.783	7.70
	28.9	205.0	0.915	9.60
	33.0	230.0	1.026	10.96
	37.4	250.0	1.115	12.42
	42.9	272.0	1.213	14.25
29	13.7	174.0	0.777	4.55
	18.1	217.0	0.967	6.01
	27.2	276.0	1.23	9.03
	34.7	320.5	1.43	11.53
	39.3	348.5	1.555	13.06
25	17.1	305.5	1.363	5.68
	23.5	362.0	1.615	7.80
	31.0	419.5	1.870	10.32
	40.4	485.0	2.16	13.42

TABLE VI

Rheological Properties of Redwater Crude Oil, Test No. 3

Thermal History: Sample obtained at approximately 50°F, warmed to 70°F, cooled successively to indicated temperature.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
60	16.4	8.3	0.037	5.44
	23.4	12.3	0.055	7.77
	32.35	16.5	0.074	10.74
	41.0	21.0	0.094	13.62
50	17.0	13.5	0.060	5.64
	26.2	19.5	0.087	8.70
	35.65	25.5	0.113	11.84
	41.6	30.0	0.134	13.80
40	13.95	25.5	0.114	4.63
	19.9	35.0	0.156	6.61
	25.9	46.0	0.205	8.60
	30.75	52.5	0.234	10.28
	37.7	62.7	0.279	12.52
	43.4	67.5	0.301	14.40
35	14	44.7	0.199	4.65
	21.8	69.3	0.309	7.23
	26.7	87.3	0.389	8.86
	32.1	103.8	0.463	10.66
	37.4	118.0	0.526	12.42
	46.5	141.5	0.631	15.44
30	14.15	107.5	0.479	4.70
	22.3	155.0	0.691	7.40
	29.1	196.0	0.873	9.66
	36.5	231.0	1.030	12.12
	45.5	268.0	1.195	15.10
22	14.1	214.0	0.954	4.68
	22.9	294.0	1.310	7.60
	30.0	362.5	1.615	9.96
	37.0	415.0	1.850	12.28
	46.0	482.0	2.150	15.27

Wax deposition was noted at temperatures below 30°F.

TABLE VII

Rheological Properties of Redwater Crude Oil, Test No. 4

Thermal History: Sample obtained at approximately 50°F, precooled to 50°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
15.5	14.2	84.0	0.374	4.72
	27.0	149.7	0.667	8.96
	32.1	172.3	0.768	10.65
	38.0	204.0	0.910	12.62
20	14.2	76.0	0.339	4.72
	21	107.3	0.478	6.98
	27.2	127.5	0.568	9.03
	33.4	157.0	0.700	11.09
	40.5	182.0	0.812	13.45
	45.2	193.0	0.860	15.00
24.5	14.15	58.0	0.258	4.70
	21.3	81.7	0.364	7.07
	28.9	106.0	0.473	9.60
	35.8	128.0	0.570	11.88
	39.9	145.5	0.648	13.25
	42.8	149.0	0.664	14.20
30	14.05	46.5	0.207	4.67
	25.9	78.0	0.348	8.60
	32.2	94.7	0.422	10.70
	37.9	104.8	0.467	12.60
	43.4	119.0	0.530	14.40
32.5	14.1	38.3	0.171	4.68
	24.25	63.0	0.281	8.05
	31.8	80.5	0.359	10.56
	39.2	95.0	0.423	13.03
	40.5	96.8	0.431	13.45
35	13.95	32.5	0.145	4.63
	24.8	57.0	0.254	8.23
	31.8	73.5	0.328	10.56
	38.2	81.7	0.364	12.70
	44.0	93.5	0.417	14.60

Wax deposition was noted at temperatures below 35°F.

TABLE VII (continued)

Rheological Properties of Redwater Crude Oil, Test No. 4

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
37.5	14.05	26.0	0.116	4.67
	25.0	43.0	0.192	8.30
	31.6	53.5	0.238	10.50
	38.6	65.5	0.292	12.82
	39.7	67.0	0.298	13.18
40	15.8	22.3	0.099	5.24
	24.1	36.5	0.163	8.00
	30.5	47.5	0.212	10.30
	37.3	56.5	0.252	12.39
	37.7	57.5	0.256	12.52
50	14.1	18.3	0.082	4.68
	21.9	27.7	0.124	7.27
	30.6	39.2	0.175	10.50
	39.5	49.0	0.218	13.12
	44.8	53.0	0.236	14.90
60	14.0	13.5	0.060	4.65
	22.2	20.2	0.090	7.37
	29.7	27.5	0.125	9.86
	35.5	32.7	0.146	11.80
	46.2	42.0	0.187	12.02
70	14.05	9.5	0.042	4.67
	23.2	16.7	0.075	7.70
	29.5	20.6	0.092	9.80
	35.0	23.7	0.106	11.62
	40.4	27.5	0.123	13.40

Wax deposition was noted at temperatures below 35°F.

TABLE VIII

Rheological Properties of Redwater Crude Oil, Test No. 5

Thermal History: Sample obtained at approximately 50°F., warmed to 70°F., cooled successively to indicated temperature.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
70	13.9	6.3	0.028	4.62
	18.3	8.5	0.038	6.07
	24.1	11.0	0.049	8.00
	26.0	12.2	0.054	8.63
	29.8	14.0	0.062	9.90
	32.6	15.4	0.069	10.83
	37.5	17.0	0.076	12.43
	40.6	17.5	0.078	13.47
60	13.9	8.5	0.038	4.62
	19.7	12.5	0.056	6.54
	26.9	16.5	0.074	8.93
	32.3	20.8	0.093	10.73
	37.9	24.8	0.111	12.59
	42.8	27.5	0.123	14.20
50	14.2	13.5	0.060	4.72
	20.7	21.0	0.094	6.87
	25.9	27.0	0.120	8.60
	31.1	32.5	0.145	10.35
	35.3	37.5	0.167	11.72
	45.5	47.0	0.209	15.10
35	14.0	56.0	0.250	4.65
	20.1	81.0	0.361	6.67
	26.4	106.5	0.475	8.77
	31.8	129.0	0.575	10.57
	36.7	146.0	0.650	12.18
	43.9	168.0	0.750	14.60
20	14.55	229.0	1.020	4.83
	17.4	274.3	1.224	5.78
	22.85	330.0	1.470	7.58
	23.8	371.3	1.663	7.90

Wax deposition was noted at temperatures below 30°F.

Rheological Properties of Redwater Crude Oil, Test No. 6

Thermal History: Sample precooled at 50°F for 6 hours, supernatant liquid decantant off and tested at the successively increasing temperatures as indicated.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
15	15.0	110.5	0.492	4.98
	19.65	146.0	0.650	6.53
	23.4	162.0	0.722	7.77
	26.0	191.0	0.851	8.63
	32.5	223.5	0.996	10.80
	37.9	253.0	1.127	12.58
	43.0	274.0	1.220	14.28
25	14.1	63.3	0.282	4.68
	17.9	81.3	0.362	5.94
	24.7	101.0	0.450	8.20
	27.0	106.0	0.472	8.96
	33.8	125.9	0.561	11.22
	41.4	151.5	0.675	13.75
35	14.05	35.3	0.157	4.66
	20.15	47.0	0.209	6.70
	25.6	58.0	0.258	8.50
	30.5	66.0	0.294	10.30
	36.7	76.5	0.341	12.20
	39.8	81.3	0.362	13.22
38.5	14.05	26.5	0.118	4.67
	21.0	36.5	0.163	6.97
	27.1	46.3	0.206	9.00
	33.8	54.7	0.244	11.23
	39.3	63.2	0.282	13.05
	41.3	65.3	0.291	13.70
42	14.0	21.3	0.095	4.65
	20.9	30.5	0.136	6.94
	27.7	39.0	0.174	9.20
	33.3	47.0	0.209	11.05
	40.8	56.5	0.252	13.55
55	14.1	12.5	0.056	4.68
	21.5	18.7	0.083	7.13
	28.3	25.0	0.112	9.40
	34.8	30.0	0.134	11.56
	42.7	35.5	0.158	14.18
60	14.1	11.0	0.049	4.68
	23.4	17.5	0.078	7.77
	29.2	21.5	0.096	9.70
	35.0	26.0	0.116	11.62

Wax deposition was noted at temperatures below 35 F.

TABLE X

Rheological Properties of Joseph Lake Crude Oil, Test No. 1

Thermal History: Sample obtained at 50°F, warmed to 70°F, cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
65	12.9	4.0	0.018	4.28
	21.1	7.3	0.033	7.00
	29.6	10.5	0.047	9.83
	35.3	13.0	0.058	11.72
	44.6	16.3	0.073	14.80
49	13.2	61.0	0.272	4.38
	24.5	99.0	0.442	8.13
	21.6	113.5	0.506	10.50
	37.7	120.0	0.535	12.52
	44.2	131.0	0.584	14.68
40	13.3	103.0	0.459	4.42
	21.2	143.3	0.639	7.04
	28.5	167.3	0.746	9.46
	35.7	184.0	0.820	11.85
	45.8	210.0	0.936	15.2
30	13.2	173.0	0.771	4.38
	21.6	201.0	0.895	7.17
	26.2	263.0	1.172	8.70
	33.0	291.0	1.293	10.95
	45.7	344.0	1.534	15.16
25 (2.6 cm. immersion)	13.2	177.5	1.067	4.38
	20.5	232.5	1.398	6.80
	31.4	290.0	1.745	10.43
	46.6	355.0	2.135	15.47

Wax deposition was noted at temperatures below 25°F.

TABLE XI

Rheological Properties of Joseph Lake Crude Oil, Test No. 2

Thermal History: Sample obtained at approximately 50°F, precooled to 50°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
15.5 (1.6 cm.immersion)	13.6	118.0	1.095	4.52
	20.3	144.5	1.342	6.74
	27.9	168.0	1.560	9.27
	33.8	182.0	1.690	11.22
	41.0	196.5	1.824	13.60
20 (1.6 cm.immersion)	13.4	77.0	0.715	4.45
	21.0	105.0	0.975	6.97
	27.8	121.0	1.123	9.23
	33.1	140.0	1.300	11.00
	37.4	147.5	1.370	12.42
	42.6	160.0	1.485	14.14
26 (2.6 cm.immersion)	13.3	146.5	0.882	4.42
	17.4	162.3	0.977	5.78
	25.0	187.5	1.128	8.30
	30.8	196.5	1.183	10.56
	36.0	202.0	1.215	11.95
	45.2	222.5	1.340	15.00
29.5	13.3	204.0	0.910	4.42
	20.0	251.5	1.120	6.64
	28.0	294.0	1.310	9.30
	33.7	313.0	1.395	11.18
39.5	13.2	96.5	0.430	4.38
	20.9	135.5	0.604	6.94
	28.1	151.5	0.675	9.33
	33.9	159.5	0.711	11.26
	38.0	162.0	0.722	12.62
	44.8	166.0	0.740	14.87
50	13.2	35.0	0.156	4.38
	20.0	42.0	0.187	6.64
	26.5	50.5	0.225	8.80
	31.8	57.0	0.254	10.56
	43.3	65.0	0.290	14.40

Considerable wax deposition was noted at temperatures below 35 F.

TABLE XII

Rheological Properties of Excelsior D2 Crude Oil, Test No.1

Thermal History: Sample obtained at approximately 50°F, precooled to 10°F, and warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
13	13.3	36.0	0.161	4.42
	21.0	52.5	0.234	6.98
	28.7	68.0	0.303	9.53
	33.2	75.5	0.336	11.03
	43.8	96.5	0.430	14.55
21	13.1	27.5	0.123	4.35
	24.0	40.0	0.178	7.97
	28.5	52.0	0.232	9.47
	33.3	59.0	0.263	11.07
30	13.15	20.0	0.089	4.37
	20.0	29.5	0.132	6.64
	28.0	36.5	0.163	9.30
	33.6	44.5	0.198	11.17
	46.7	61.0	0.272	15.5
40	13.15	16.0	0.071	4.37
	22.65	24.7	0.110	7.52
	29.4	31.0	0.138	9.77
	33.9	36.5	0.163	11.26
	46.0	48.0	0.214	15.28
49	13.2	10.5	0.047	4.38
	21.6	20.0	0.089	7.17
	27.5	22.0	0.098	9.13
	33.9	27.0	0.120	11.26
	46.2	37.0	0.165	15.33

A little waxing was noted at temperatures below 20°F.

TABLE XIII

Rheological Properties of Excelsior D2 Crude Oil, Test No. 2

Thermal History: Sample obtained at approximately 50°F, warmed to 60°F, cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
49	13.45	7.0	0.031	4.47
	21.1	10.5	0.047	7.00
	28.2	14.5	0.065	9.37
	34.9	19.0	0.085	11.60
	44.0	24.0	0.107	14.60
40	13.3	10.5	0.047	4.42
	20.9	16.0	0.071	6.94
	29.7	22.5	0.100	9.87
	36.0	28.0	0.125	11.96
	46.0	35.0	0.156	15.28
30	13.3	19.0	0.085	4.42
	22.0	30.5	0.136	7.30
	29.5	40.5	0.181	9.80
	35.7	48.5	0.216	11.85
	45.6	61.0	0.272	15.13
20	13.3	35.0	0.156	4.42
	21.3	52.5	0.234	7.07
	30.2	72.0	0.321	10.05
	36.8	87.0	0.388	12.23
	46.8	108.0	0.482	15.55
11	13.2	55.5	0.247	4.38
	22.3	85.5	0.381	7.41
	30.3	111.5	0.497	10.10
	38.2	136.5	0.608	12.70
	46.7	157.0	0.700	15.5

No waxing noted.

TABLE IV

Rheological Properties of Leduc D2 Crude Oil, Test No. 1

Thermal History: Sample obtained at approximately 50°F, cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
40	13.4	6.5	0.029	4.45
	22.7	12.5	0.056	7.54
	31.0	16.0	0.071	10.33
	36.5	19.5	0.087	12.12
	45.1	24.0	0.107	15.00
27	13.2	22.0	0.098	4.38
	22.4	39.0	0.174	7.44
	28.8	44.0	0.196	9.56
	33.7	48.0	0.214	11.20
	45.0	56.5	0.252	14.95
20	13.2	32.0	0.143	4.38
	20.8	48.0	0.214	6.91
	29.0	62.5	0.279	9.64
	35.8	71.0	0.316	11.90
	44.2	77.5	0.345	14.68
9	15.4	54.0	0.241	5.12
	22.8	83.0	0.370	7.57
	29.8	98.5	0.439	9.90
	35.7	112.5	0.502	11.86
	40.3	119.5	0.533	13.40

No waxing noted.

TABLE XV

Rheological Properties of Leduc D2 Crude Oil, Test No. 2

Thermal History: Sample obtained at approximately 50°F, precooled to 0°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
3	13.3	31.5	0.140	4.42
	19.7	42.5	0.190	6.54
	26.3	53.0	0.236	8.73
	32.7	62.0	0.276	10.87
	37.3	70.0	0.312	12.40
	40.0	72.0	0.321	13.28
11	13.2	29.0	0.129	4.38
	22.1	43.0	0.192	7.34
	27.9	53.0	0.236	9.27
	34.2	58.5	0.261	11.37
18	13.2	19.5	0.087	4.38
	21.2	27.5	0.123	7.04
	29.7	37.0	0.165	9.87
	38.0	46.0	0.205	12.63
	41.5	50.5	0.225	13.78
25	13.2	14.0	0.063	4.38
	22.3	22.5	0.100	7.40
	31.2	29.0	0.129	10.38
	35.9	33.0	0.147	11.93
	40.3	37.5	0.167	13.40
31	13.2	11.0	0.049	4.38
	21.4	18.0	0.080	7.11
	29.0	23.0	0.103	9.63
	33.9	26.5	0.112	11.26
	39.2	31.5	0.141	13.02
39	13.2	9.5	0.042	4.38
	21.4	13.5	0.060	7.11
	28.7	18.0	0.080	9.53
	34.7	21.5	0.096	11.52
	38.0	24.5	0.109	12.63
48	13.2	8.0	0.036	4.38
	24.5	13.0	0.058	8.13
	30.9	15.0	0.067	10.3
	38.6	18.0	0.080	12.82

No waxing noted.

TABLE XVI

Rheological Properties of Golden Spike Crude Oil, Test No. 1

Thermal history: Sample obtained at approximately 50°F, warmed to 70°F, cooled successively to indicated temperature.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
57	12.5	6.0	0.027	4.15
	22.4	10.0	0.045	7.44
	30.2	13.5	0.060	10.05
	35.9	17.0	0.076	11.93
45	12.9	14.5	0.065	4.28
	21.8	24.5	0.109	7.24
	29.5	33.5	0.149	9.80
	35.5	41.0	0.183	11.79
	36.8	42.0	0.187	12.22
35	13.0	50.5	0.225	4.32
	24.5	78.5	0.350	8.13
	31.0	90.0	0.401	10.32
	37.3	100.5	0.448	12.39
	39.1	110.0	0.491	12.98
28	12.9	69.0	0.308	4.28
	21.4	97.5	0.434	7.11
	29.1	124.5	0.555	9.66
	34.5	140.5	0.627	11.45
	38.0	155.0	0.691	12.62
21	12.9	95.5	0.426	4.28
	21.4	139.0	0.620	7.11
	29.0	179.0	0.798	9.63
	35.3	200.5	0.894	11.73
14.5	12.9	123.0	0.548	4.28
	22.0	186.0	0.830	7.31
	29.3	227.5	1.014	9.73
	34.4	255.5	1.040	11.42
	35.7	258.0	1.150	11.85
8	12.9	154.0	0.687	4.28
	17.9	203.5	0.907	5.94
	32.0	271.0	1.210	10.63
	32.1	308.0	1.373	10.67
	35.1	314.0	1.400	11.67

No waxing noted.

TABLE XVIII

Rheological Properties of Golden Spike Crude Oil, Test No. 2

Thermal History: Sample received at approximately 50°F, precooled to 0°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
3.5	13.05	57.5	0.256	4.33
	21.1	82.5	0.368	7.01
	29.7	114.0	0.508	9.87
	36.5	131.0	0.583	12.13
10.5	13.0	52.5	0.234	4.32
	20.9	74.0	0.330	6.94
	23.4	86.0	0.383	7.77
	33.3	98.0	0.437	11.06
18	13.0	35.0	0.156	4.32
	19.6	48.0	0.214	6.51
	26.9	62.5	0.278	8.93
	32.6	75.5	0.336	10.83
	35.2	82.0	0.365	11.70
25	12.9	26.0	0.116	4.28
	23.1	42.5	0.189	7.67
	28.9	51.0	0.227	9.60
	33.7	58.5	0.261	11.20
	36.4	66.0	0.294	12.08
30	13.1	22.5	0.100	4.35
	21.0	33.5	0.150	6.98
	29.0	45.5	0.203	9.63
	35.1	55.0	0.245	11.66
	35.9	55.0	0.245	11.93
39	13.0	17.5	0.078	4.32
	21.5	26.5	0.118	7.14
	29.8	35.5	0.158	9.90
	36.3	42.0	0.187	12.06
50	13.0	12.0	0.054	4.32
	21.7	19.0	0.085	7.20
	29.4	25.0	0.112	9.77
	35.6	30.0	0.134	11.82
	38.0	32.0	0.143	12.62

No waxing noted.

TABLE XVIII

Rheological Properties of Duhamel D2 Crude Oil, Test No. 1

Thermal History: Sample obtained at 50 - 60°F, precooled to -10°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
-7	13.15	24.5	0.109	4.37
	21.8	40.0	0.178	7.24
	28.3	52.5	0.234	9.40
	34.2	63.0	0.281	11.37
	40.4	75.5	0.336	13.43
6	13.1	22.5	0.100	4.35
	20.7	32.0	0.143	6.87
	28.6	41.5	0.185	9.53
	34.2	51.0	0.227	11.35
	39.4	58.0	0.258	13.10
15	13.0	17.5	0.0780	4.32
	20.8	27.0	0.120	6.90
	26.8	34.5	0.154	8.90
	33.0	41.5	0.185	10.95
	40.0	47.5	0.212	13.30
25	13.1	14.0	0.0624	4.35
	20.8	21.0	0.0936	6.90
	29.0	29.0	0.129	9.63
	34.6	34.5	0.154	11.50
	39.3	40.0	0.178	13.07
35	13.0	10.5	0.0448	4.32
	22.0	18.0	0.0803	7.30
	30.7	25.0	0.1115	10.20
	36.8	29.0	0.129	12.20
	38.4	30.5	0.136	12.75
45	13.05	8.5	0.0379	4.33
	23.2	14.5	0.0646	7.70
	30.2	19.5	0.0869	10.03
	35.0	23.0	0.1025	11.63
	43.2	28.5	0.127	14.35
55	13.15	7.0	0.0312	4.37
	20.6	10.5	0.0468	6.84
	28.2	15.0	0.0669	9.36
	34.4	19.0	0.0847	11.43
	40.8	22.5	0.1005	13.56
65	13.0	6.5	0.0290	4.32
	21.6	10.5	0.0468	7.17
	29.7	13.5	0.0602	9.86
	35.7	16.5	0.0735	11.85
	42.0	20.0	0.0892	13.95

No waxing noted.

TABLE XIX

Rheological Properties of Duhamel D2 Crude Oil, Test No. 2

Thermal History: Sample obtained at 50 - 60°F, warmed to 70°F,
cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
69	13.45	3.5	0.0156	4.47
	22.6	6.5	0.0290	7.50
	28.5	8.5	0.0379	9.46
	34.2	10.0	0.0446	11.36
	42.7	13.0	0.0580	14.18
59	13.0	3.5	0.0156	4.32
	21.2	6.5	0.0290	7.04
	29.6	10.0	0.0446	9.83
	34.4	11.5	0.0513	11.42
	41.0	15.0	0.0669	13.62
48	12.9	5.0	0.0223	4.28
	22.5	9.5	0.0423	7.47
	29.2	12.5	0.0557	9.70
	34.9	15.5	0.0691	11.58
	40.2	18.3	0.0816	13.35
38	12.9	8.5	0.0379	4.28
	24.5	16.5	0.0736	8.13
	30.3	20.5	0.0914	10.06
	35.0	24.0	0.107	10.62
	39.4	28.0	0.125	13.09
29	12.9	13.0	0.0580	4.28
	21.7	22.0	0.0981	7.20
	29.7	30.0	0.134	9.86
	35.2	36.5	0.163	11.70
	40.0	41.5	0.185	13.30
20	12.9	21.5	0.0954	4.28
	21.6	34.0	0.152	7.17
	30.3	46.5	0.207	10.06
	35.0	53.0	0.236	11.62
	40.0	60.0	0.267	13.29
9	13.0	32.0	0.143	4.32
	21.7	52.5	0.234	7.20
	29.3	68.5	0.305	9.73
	35.5	82.5	0.368	11.78
	40.7	93.0	0.414	13.50
2	13.0	43.5	0.194	4.32
	20.8	65.5	0.292	6.91
	28.0	82.5	0.368	9.30
	33.3	96.5	0.430	11.06
	40.5	117.0	0.522	13.45

No waxing noted.

TABLE XX

Rheological Properties of Duhamel D3 Crude Oil, Test No. 1

Thermal History: Sample obtained at 50 - 60°F, precooled to 0°F, warmed successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
10	13.1	102.0	0.455	4.35
	22.2	157.0	0.700	7.37
	31.6	185.0	0.825	10.50
	35.6	212.0	0.945	11.72
	40.5	228.0	1.16	13.45
21	13.2	75.0	0.334	4.36
	22.1	105.0	0.468	7.33
	30.7	136.5	0.608	10.20
	35.1	145.0	0.647	11.65
	43.0	167.0	0.745	14.30
30	13.1	49.0	0.218	4.35
	22.6	74.5	0.332	7.50
	31.2	95.0	0.423	10.37
	38.0	106.0	0.473	12.62
	42.0	116.0	0.517	13.95
40	13.1	32.0	0.143	4.37
	22.5	47.5	0.212	7.47
	31.0	59.5	0.265	10.32
	37.1	67.5	0.301	12.32
	43.8	76.5	0.341	14.55
50	13.1	13.0	0.0803	4.33
	23.4	29.5	0.1315	7.77
	31.3	37.0	0.165	10.40
	38.4	45.5	0.203	12.77
	43.6	47.5	0.212	14.47
60	13.1	11.0	0.0490	4.35
	23.1	18.5	0.0825	7.67
	31.0	24.0	0.107	10.33
	42.0	30.5	0.136	13.95

Waxing noted below 30°F.

TABLE XXI

Rheological Properties of Duhamel D3 Crude Oil, Test No. 2

Thermal History: Sample obtained at 50 - 60°F, warmed to 70°F,
and cooled successively to indicated temperatures.

Temperature °F	Rotational Speed r.p.m.	Deflection degrees	Shearing Stress lb./ft.sec. ²	Rate of Shear sec. ⁻¹
66	13.6	4.5	0.0201	4.50
	23.0	8.0	0.0357	7.63
	31.2	12.0	0.0535	10.37
	37.7	15.0	0.0669	12.52
	44.0	18.0	0.0803	14.60
55	13.2	4.5	0.0201	4.37
	22.9	11.5	0.0513	7.60
	31.5	17.5	0.0780	10.45
	38.1	23.0	0.103	12.66
	42.8	28.5	0.191	14.20
45	13.1	22.5	0.1004	4.32
	23.7	43.5	0.194	7.87
	32.0	59.0	0.263	10.33
	38.9	74.0	0.330	12.92
	43.7	85.0	0.379	14.50
35	13.1	70.0	0.312	4.35
	23.0	112.0	0.500	7.63
	32.2	146.0	0.650	10.37
	38.4	164.5	0.733	12.76
	43.8	182.5	0.813	14.55
25	13.1	175.0	0.780	4.35
	23.7	258.5	1.152	7.87
	33.7	323.0	1.44	11.18
	42.2	367.0	1.635	14.00
15	13.1	142.0	0.855	4.35
	26.6	230.0	1.385	8.83
	35.3	267.0	1.607	11.73
	43.2	298.5	1.80	14.33
11	13.1	168.5	1.015	4.35
	25.2	282.0	1.70	8.37
	32.0	329.5	1.985	10.63
	40.3	371.5	2.235	13.40

Waxing noted below 20°F.

APPENDIX C

DERIVED DATA: APPARENT VISCOSITY
VERSUS RATE OF SHEAR AND TEMPERATURE

TABLE XXII

Apparent Viscosity (lbs./ft.sec.) Versus Rate of Shear
and Temperature

<u>Crude Oil</u>	<u>Rate of Shear</u> <u>sec.⁻¹</u>	<u>Temperature °F</u>						
		<u>50</u>	<u>40</u>	<u>35</u>	<u>30</u>	<u>25</u>	<u>20</u>	<u>15</u>
Redwater Test No. 1	15	0.0167	0.0191	0.0271	0.0362	0.0452	0.0525	0.0590
	10	0.0167	0.0191	0.0280	0.0370	0.0470	0.0548	0.0623
	5	0.0167	0.0191	0.0307	0.0400	0.0520	0.0608	0.0710
	2.5	0.0167	0.0191	0.0340	0.0440	0.0592	0.0692	0.0837
		<u>70</u>	<u>60</u>	<u>50</u>	<u>40</u>	<u>37</u>	<u>35</u>	<u>33</u>
Redwater Test No. 2	15	0.0055	0.0095	0.0160	0.0458	0.0578	0.0740	0.080 0.114
	10	0.0055	0.0095	0.0175	0.0480	0.0630	0.0830	0.094
	5	0.0055	0.0095	0.0220	0.0540	0.0774	0.0990	0.110
	2.5	0.0055	0.0095	0.0268	0.0640	0.0920	0.116	0.130
		<u>29</u>	<u>25</u>					
		0.114	0.167					
		0.133	0.184					
		0.170	0.254					
		0.200	0.309					
		<u>60</u>	<u>50</u>	<u>40</u>	<u>35</u>	<u>30</u>	<u>22</u>	
Redwater Test No. 3	15	0.0070	0.0100	0.0213	0.0423	0.0820	0.142	
	10	0.0070	0.0100	0.0225	0.0435	0.0880	0.162	
	5	0.0070	0.0100	0.0254	0.0450	0.100	0.200	
	2.5	0.0070	0.0100	0.0300	0.0485	0.113	0.225	
		<u>70</u>	<u>60</u>	<u>50</u>	<u>40</u>	<u>37.5</u>	<u>35</u>	<u>32.5</u>
Redwater Test No. 4	15	0.0093	0.0125	0.0168	0.0205	0.0225	0.0285	0.0320
	10	0.0093	0.0125	0.0168	0.0205	0.0230	0.0230	0.0338
	5	0.0093	0.0125	0.0168	0.0205	0.0248	0.0328	0.0370
	2.5	0.0093	0.0125	0.0168	0.0205	0.0268	0.0360	0.0405
		<u>30</u>	<u>24.5</u>	<u>20</u>	<u>15.5</u>			
		0.0365	0.0467	0.0567	0.0713			
		0.0393	0.0490	0.0625	0.0730			
		0.0446	0.0546	0.0710	0.0793			
		0.0512	0.0620	0.0824	0.0908			

TABLE XXII (continued)

Apparent Viscosity (lbs./ft.sec.) Versus Rate of Shearand TemperatureTemperature of

<u>Crude Oil</u>	<u>Rate of Shear</u> <u>sec.⁻¹</u>	<u>70</u>	<u>60</u>	<u>50</u>	<u>35</u>	<u>20</u>		
Redwater Test No. 5	15	0.0061	0.0087	0.0139	0.0517	0.185		
	10	"	"	"	0.0537	0.196		
	5	"	"	"	0.0564	0.213		
	2.5	"	"	"	0.0580	0.240		
		<u>60</u>	<u>55</u>	<u>42</u>	<u>38.5</u>	<u>35</u>	<u>25</u>	<u>15</u>
Redwater Test No. 6	15	0.0095	0.0112	0.0184	0.0217	0.0274	0.0475	0.085
	10	"	"	0.0187	0.0225	0.0287	0.0520	0.094
	5	"	"	0.0210	0.0240	0.0334	0.0646	0.110
	2.5	"	"	0.0240	0.0280	0.0356	0.0748	0.127
		<u>65</u>	<u>49</u>	<u>40</u>	<u>30</u>	<u>25</u>		
Joseph Lake Test No. 1	15	0.005	0.0334	0.0631	0.1015	0.142		
	10	"	0.0488	0.0760	0.124	0.168		
	5	"	0.0674	0.1070	0.184	0.235		
	2.5	"	0.0872	0.140	0.248	0.290		
		<u>50</u>	<u>39.5</u>	<u>20</u>	<u>15.5</u>			
Joseph Lake Test No. 2	15	0.0233	0.0512	0.103	0.129			
	10	0.0245	0.0687	0.1225	0.161			
	5	0.0320	0.103	0.1550	0.234			
	2.5	0.0400	0.115	0.1630	0.285			
		<u>50</u>	<u>40</u>	<u>30</u>	<u>21</u>	<u>13</u>		
Excelsior D2 Test No. 1	15	0.0108	0.0141	0.0175	0.023	0.0295		
	10	"	0.0146	0.0182	0.024	0.0323		
	5	"	0.0160	0.0200	0.030	0.0356		
	2.5	"	0.0180	0.0224	0.033	0.0420		
		<u>49</u>	<u>40</u>	<u>30</u>	<u>20</u>	<u>11</u>		
Excelsior D2 Test No. 2	15	0.007	0.0102	0.0181	0.0313	0.0477		
	10	"	"	0.0184	0.0320	0.0497		
	5	"	"	0.0192	0.0340	0.0550		
	2.5	"	"	0.0200	0.0372	0.0640		

TABLE XXII (continued)

Apparent Viscosity (lbs./ft.sec.) Versus Rate of Shearand Temperature

Temperature °F

<u>Crude Oil</u>	<u>Rate of Shear sec.⁻¹</u>	<u>40</u>	<u>27</u>	<u>20</u>	<u>9</u>			
Leduc D2								
Test No. 1	15	0.0068	0.0169	0.0248	0.0396			
	10	"	0.0204	0.0276	0.0444			
	5	"	0.0280	0.0350	0.0574			
	2.5	"	0.0360	0.0424	0.0760			
		<u>48</u>	<u>39</u>	<u>31</u>	<u>25</u>	<u>18</u>	<u>11</u>	<u>3</u>
Leduc D2								
Test No. 2	15	0.00633	0.0084	0.0107	0.0120	0.0159	0.0217	0.0241
	10	"	"	0.0109	0.0125	0.0167	0.0237	0.0262
	5	"	"	0.0114	0.0140	0.0190	0.0280	0.0314
	2.5	"	"	0.0120	0.0160	0.0220	0.0340	0.0380
		<u>57</u>	<u>45</u>	<u>35</u>	<u>28</u>	<u>21</u>	<u>14.5</u>	<u>8</u>
Golden Spike								
Test No. 1	15	0.068	0.150	0.347	0.534	0.774	0.096	0.119
	10	"	"	0.392	0.568	0.820	0.104	0.128
	5	"	"	0.520	0.674	0.950	0.125	0.154
	2.5	"	"	0.630	0.810	0.115	0.154	0.198
		<u>50</u>	<u>39</u>	<u>30</u>	<u>25</u>	<u>18</u>	<u>10.5</u>	<u>3.5</u>
Golden Spike								
Test No. 2	15	0.0115	0.0154	0.0203	0.0228	0.0300	0.0405	0.0463
	10	"	0.0160	0.0207	0.0237	0.0313	0.0431	0.0490
	5	"	0.0174	0.0224	0.0264	0.0350	0.0510	0.0574
	2.5	"	0.0192	0.0240	0.0300	0.0400	0.0620	0.0700
		<u>65</u>	<u>55</u>	<u>45</u>	<u>35</u>	<u>25</u>	<u>15</u>	<u>6</u>
Duhamel D2								
Test No. 1	15	0.0063	0.0073	0.0088	0.0108	0.0134	0.0171	0.0200
	10	"	"	"	"	"	"	"
	5	"	"	"	"	"	"	"
	2.5	"	"	"	"	"	"	"

TABLE XXII (continued)

Apparent Viscosity (lbs./ft.sec.) Versus Rate of Shearand Temperature

Temperature °F

<u>Crude Oil</u>	<u>Rate of Shear sec.⁻¹</u>	<u>69</u>	<u>59</u>	<u>48</u>	<u>38</u>	<u>29</u>	<u>20</u>	<u>9</u>	<u>2</u>
Duhamel D2 Test No. 2	15	0.0041	0.0048	0.0061	0.0094	0.0139	0.0200	0.0307	0.0384
	10	"	"	"	"	"	0.0205	0.0313	0.0397
	5	"	"	"	"	"	0.0220	0.0330	0.0440
	2.5	"	"	"	"	"	0.0240	0.0348	0.0500
		<u>60</u>	<u>50</u>	<u>40</u>	<u>30</u>	<u>21</u>	<u>10</u>		
Duhamel D3 Test No. 1	15	0.0101	0.0145	0.0233	0.0364	0.0520	0.075		
	10	"	0.0159	0.0259	0.0405	0.0576	0.0808		
	5	"	0.0188	0.0318	0.0494	0.0704	0.100		
	2.5	"	0.0220	0.0380	0.0608	0.0950	0.132		
		<u>66</u>	<u>55</u>	<u>45</u>	<u>35</u>	<u>25</u>	<u>15</u>	<u>11</u>	
Duhamel D3 Test No. 2	15	0.006	0.0083	0.0255	0.0557	0.114	0.125	0.163	
	10	"	"	"	0.0612	0.133	0.147	0.188	
	5	"	"	"	0.0720	0.173	0.188	0.257	
	2.5	"	"	"	0.0872	0.210	0.240	0.320	

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